Infiltration Research Planning Workshop

Part I. State of the Art Reports

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FOREWORD

The workshop objective was to review briefly the state of the art regarding knowledge of the infiltration mechanism and to begin development of a SEA research plan to expand that knowledge. Participants were asked to prepare short state-of-the-art papers relating to various aspects of infiltration. Part I presents these papers. Part II will present results of the planning task, which is still in progress at this time.

The papers present views of the individual authors and not necessarily those of the U.S. Department of Agriculture. Each paper is brief, but they provide a comprehensive overview of infiltration knowledge today and contain lists of references for readers interested in expanding their knowledge further. Copies are available from

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CONTENTS

EMPIRICAL AND SIMPLIFIED MODELS OF THE INFILTRATION PROCESS

D. L. Brakensiek

We would probably be tempted to say we are in an era of unprecedented infiltration research activity. First, though, we might recall a statement in the report of the Committee on Infiltration, 1945-46, of the American Geophysical Union. A paper by H. L. Cook (1946) included in the committee report began with the sentence, "Some future historian of the development of scientific hydrology will probably be tempted to call the present period the 'era of infiltration'." Obviously, this "era" will continue for the foreseeable future or as long as research continues in scientific hydrology.

In this brief report, a sample of reported infiltration research was selected to stimulate our discussions in the areas of--

- the rainfall infiltration problem
- infiltration models
    - empirical equations
    - approximations of more rigorous flow equations
    - equations derived from simplifications of the physical system
- testing and comparison of models
- estimation of model parameters
- watershed retention.

THE RAINFALL-INFILTRATION PROBLEM

Most reported research since the Mein and Larson (1971) studies recognizes the rainfall-infiltration process to be rainfall-rate controlled until surface saturation (ponding) occurs, and after ponding being controlled by the soil "hydraulic" properties. The work of Smith (1972, 1973) and Smith and Parlange (1977) also derived models that predict ponding time and infiltration after ponding. Childs (1969) described the infiltration process--"the infiltration rate may be regarded either as the consequence of the hydraulic conductivity and the potential gradient at the surface in accordance with Darcy's Law *or alternatively as the rate of increase of the total amount of water stored in the soil profile.*" (Italics mine.) With the latter view, rainfall infiltration is simply handled by the relationship between infiltration rate and the corresponding accumulated infiltration at that rate, which then treats the pre- and post-ponding infiltration as a continuum. Thus, any infiltration rate equation and its integral can be applied to any rainfall rate-time distribution without regard, of course, to actual clock time. Questions of breaks within the rainfall distribution and subsequent redistribution are obviously important aspects still to be considered.

INFILTRATION MODELS (ALGEBRAIC AND EMPIRICAL)

Most infiltration equations (those models that can be written in closed form) can be considered algebraic. Empirical is used in the sense that the equation parameters are estimated by some statistical procedure applied to time-infiltration (rate or amount) data. Some of these algebraic equations are, of course, physically based equations that can be applied empirically.

The problem with this approach is that every application is a model calibration problem utilizing infiltration or watershed data. There is always the hope that after sufficient study, parameter prediction equations will be developed. Unfortunately, this hardly ever happens.

Infiltration models that are algebraic or can be used in the algebraic and empirical sense include those developed by Brutsaert (1977), Green and Ampt (1911), Holtan (1961), Overton (1964), Philip (two parameter) (1969), Smith (1972), Horton (1940), and Kostiakov (1932). This writer would recommend the Philip (two parameter) or the Green and Ampt model as an algebraic infiltration equation if this approach is taken.

INFILTRATION MODELS (APPROXIMATIONS)

Approximation is used here in the sense of an approximation to the more rigorous flow equations. These models would include Brutsaert (1977), Philip (1969), Smith (1972, an empirical approximation), and Smith and Parlange (1978). Parlange (1971) derived an infiltration equation valid for all times, which for finite times agreed with the Philip solution. The Philip two-parameter model has parameters, sorptivity and effective conductivity, that can be estimated from soil-water data. The Smith and Parlange models, depending on the behavior of hydraulic conductivity (K) near saturation, appear to have applicability over a wide range of soil and hydrologic situations and are shown to give results similar to the Green and Ampt model.

INFILTRATION MODELS (SIMPLIFICATION)

Simplification is used here in the sense that the physical system has to be simplified. Of course, the soil system must be simplified in varying degrees for all formulations.

The Green and Ampt equation (1911) is derived for a simplified soil physical system. A "vast" amount of literature is available reporting on its use, comparisons with other models, and evaluating its utility to model the infiltration process. Philip (1957) derived the Green and Ampt equation for a soil for which the diffusivity function ($D(\theta)$ where θ is soil water content) may be represented as a delta function.

An infiltration equation was derived for a somewhat approximate system by Morel-Seytoux and Khanji (1974); however, it was used mainly to formulate an interpretation for the Green and Ampt effective capillary pressure parameters. Parlange (1975) assumed that D and $dK/d\theta$ are delta functions and derived a more exact type Green and Ampt model.

TESTING AND COMPARISONS OF MODELS

Bouwer (1969) utilized the Green and Ampt equation for ponded infiltration into a layered soil (decreasing conductivity). It appeared to give reasonable results.

Fok (1975), utilizing a series expansion of the Green and Ampt equation, derived the Philip two-parameter equation. Time limits are given for insuring a difference less than 17 percent or less than 5 percent. Parameter relationships are given for equation equivalence.

Li, Stevens and Simons (1976) derived both an explicit and an implicit form of the Green and Ampt equation for a homogenous soil.

Mein and Larson (1971) utilized actual soil data (five soils) to compare Green and Ampt with the Richards' equation. Depending on soil type, the comparison was fair to good. The rainfall-infiltration problem was solved in two stages, time to ponding and after ponding. A constant rainfall rate was assumed and the soil was assumed to be homogenous.

Onstad et al. (1973) compared Green and Ampt with infiltrometer (ponded) data. Comparisons were poor to good. However, parameter estimations of the Green and Ampt equations are questionable.

Parlange (1975) compared his improved Green and Ampt equation with the original. Maximum deviation was 20 percent.

Philip (1957) compared Horton, Kostiakov, Green and Ampt, and Philip equations (two parameter). The Horton and Kostiakov equations, in general, failed; Horton was worst. Green and Ampt and Philip equations were equally good.

Skaggs et al. (1969) compared Green and Ampt, Horton, Philip (two parameter) and Holtan equations by fitting to rainulator-derived infiltration data. Horton and Holtan (three-parameter equations) gave highest correlations. Green and Ampt and Philip gave essentially equal correlation. This writer would question the form of the Green and Ampt equation used for fitting. Also open to question is whether a 35-foot plot should be used as an infiltrometer even after using overland flow routing procedures to correct for runoff travel time.

Swartzendruber and Youngs (1974) numerically compared the Green and Ampt equation and the two-term Philip equation. The two were within 15.1 percent. The Philip two-term equation was recommended.

Whisler and Bouwer (1970) compared the Green and Ampt equation with the Philip two-parameter equation with numerical data. They concluded that Green and Ampt was the easiest to use and gave reasonably accurate results.

Dooge (1973) compared analytical physically-based and empirical infiltration equations under various simplifying assumptions. For small time he concluded that the various models correspond to the Kostiakov equation with an exponent of 1/2. He also discussed the usefulness in simulation studies of the relationship between the infiltration rate and the volume of actual or potential infiltration.

Smith (1976) theoretically discussed the Green and Ampt, Philip's two-parameter, SCS equation (1964a), Holtan equation, and Mein and Larson time to ponding equation. He recommends Green and Ampt or Philip's equation for an empirical engineering application. He considers physical estimation of parameters impractical.

The recent work by Smith and Parlange (1978) opens new insights into the Green and Ampt equation and defines more precisely the physical situation for which it applies. They derived alternative models depending on the behavior of K near saturation. Slow variations of K near saturation led to the Green and Ampt model. Exponential variation of K near saturation led to the Parlange (1971) model. Examples appeared to substantiate the applicability of the Green and Ampt model to hydrologic investigations.

Rawls et al. (1976), utilizing a Purdue infiltrometer, measured infiltration rates for 11 Coastal Plains soils near Tifton, Ga. An empirical comparison of the Horton, Holtan, Philip, Green and Ampt, and Snyder (1971) infiltration equations was made. Horton's and Snyder's equations, being four- and three-parameter equations, gave the highest correlation (0.86 and 0.95, respectively). The Philip and Green and Ampt (two parameters) equations were similar, with a correlation of 0.82. The Holtan equation had the lowest correlation, 0.74.

MODEL PARAMETER ESTIMATION

If infiltrometer data, i.e., infiltration rates or amounts or both, as a function of time are available, then a statistical estimate of any of the model parameters could probably be attempted (Skaggs et al., 1969). Some limited experiences by the writer (Brakensiek and Onstad, 1977) would indicate that site-to-site parameter variation is very great. Spatial distributional studies are needed.

Very similar to the above is the estimation of infiltration parameters which are components of total watershed models. Sensitivity analyses are quite valuable for identifying the overall influence of infiltration parameter errors on, say, runoff estimation.

The estimation of parameters in infiltration models that have a base in the soil physical system should proceed from measurable soil properties. For the Green and Ampt and Philip models, parameter estimation procedures that have been reported are listed:

Bouwer (1969):
- Effective capillary pressure, H_f, is the water entry value of the soil and can be estimated as 0.5 of the air-entry value.
- Effective hydraulic conductivity, K_o, can be described as the "rewet" hydraulic conductivity and can be taken as 0.5 of the saturated conductivity, K_s.
- The fillable porosity, n, can be obtained from volumetric water content before and after wetting.

Swartzendruber and Youngs (1974):
- K_o is the near saturated hydraulic conductivity.
- H_f is related to sorptivity(S); i.e., $H_f = S^2/2K_o\, n$.
- Fillable porosity is the difference between nominal saturation and the initial soil-water content.

Onstad et al. (1973):
- H_f taken as the pressure head where the time *vs.* measured pressure head function flattened out.
- K_o taken as $1/2\ K_s$.
- n calculated as $n = 0.86(1 - d/2.65) - W_a$; where d = bulk density and W_a = antecedent soil water.

Fok (1975):
- Green and Ampt identical with Philip two-parameter when,

  $H_f = S^2/2nK$

  K_o = hydraulic conductivity in the transmission zone

  n = product of total porosity and net increment of the degree of saturation

Smith and Parlange (1978)
- $\psi_{avg} = \int_{\psi_i}^{\psi_o} K_r d\psi$, where ψ_{avg} is the average capillary tension across the wetting front and K_r is relative hydraulic conductivity.

Mein and Larson (1971):
- $S_{avg} = \int_o^1 S dK_r$, where S_{avg} = Green and Ampt's parameter for capillary suction at the wetting front.

Brakensiek (1977) evaluated several schemes for estimating the capillary suction parameter utilizing the Mein and Larson data (1971). Estimated values were compared with those calculated by Morel-Seytoux and Khanji (1974). Reasonable agreement was shown by utilizing the Brooks and Corey (1964) relative conductivity function for sorption and also by calculation of relative conductivity from soil water characteristics (Jackson, 1972).

Morel-Seytoux and Khanji (1974) derived an equation for H_f. Comparisons indicated that the Mein and Larson estimation procedure is better than the Whisler and Bouwer procedure.

Philip's Two Parameter

Youngs (1968): - (In analogy with Green and Ampt)

(Sorptivity) $A = \sqrt{2nK_s P_a}$, P_a = average capillary tension across the wetting front.

$$B = 2/3\ K_s$$

Whisler and Bouwer (1970): - Parameters were determined by statistical fitting of equation to experimental data.

Smith and Parlange (1978): - Rough estimate of sorptivity:

$$S = \sqrt{2\psi_{avg} nK}$$

Brutsaert (1976): - Formulations for the sorption parameter

Watershed Retention

Snyder (1971) introduced a so-called watershed retention function. He considers this approach as macro-scale as compared to the point infiltration approach; i.e., a micro-scale approach to rainfall excess. His contention is that the macro approach is feasible, whereas the spatial integration of point infiltration is not yet feasible. The parameters of the retention model were estimated by an optimization process applied to plot data.

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HYSTERESIS AND REDISTRIBUTION OF SOIL WATER DURING DISCONTINUOUS INFILTRATION EVENTS

J. M. Hoover

This brief report considers the infiltration process with particular emphasis on the effects of hysteresis and redistribution on intermittent infiltration. Some factors affecting infiltration capacity and rate will be discussed, such as the duration of a pause in recurrent water application and the rate of redistribution within the soil profile. These relationships apply to watershed and numerical models.

This report will focus on the drying zone above the wetting front because this controls the rate and amount of infiltration possible during succeeding infiltration events. When infiltration ceases, movement of water from wetter to drier zones within the soil profile caused by matric potential gradients or gravity, or both, is called redistribution. The forces causing this water movement are (1) capillary forces above the wet zone acting toward the drying surface, (2) gravity acting downward, and (3) capillary forces below the wetting front acting downward. The effect of these forces during redistribution is to move the wet zone downward while distributing the water throughout the soil profile. After a rainfall, water at the infiltration surface continues moving downward as the wetting front continues to advance. The soil at the infiltration surface begins to dry. Redistribution starts at the cessation of infiltration and does not end when the large pores are drained but continues for considerable time. The initial rate of redistribution is dependent on the initial wetting depth, relative dryness of the bottom layers, and the hydraulic properties of the conductive soil. The redistribution rate decreases with time following cessation of infiltration because the hydraulic gradients and the hydraulic conductivity decrease with decreases in the soil water content above the wetting front.

The redistribution rate behind the wetting front can be defined according to Richards' equation by $\frac{dw}{dt} = at^{-b}$ (Richards et al., 1956), where w is the water content, t is time following cessation of infiltration, and a and b are constants related to the boundary conditions and conductance properties of the soil, or by $w = w_i \; F/(F + (B-1)A(T))^{(1/B-1)}$ developed by Gardner et al. (1970), where w is the water content after T time, F is the volume of infiltrate, B is the slope of the log-log plot of the hydraulic conductivity-water content relationship for the soil, and A is the application rate.

Darcy's Law (1856) for saturated flow in porous media may be extended to unsaturated flow by substitution of a capillary conductivity function for the hydraulic conductivity term. However, the relation between matric potential and soil wetness is not generally a single-valued function since the characteristic curve for water desorption of a saturated sample is usually different than that for water sorption by the initially dry sample. In 1930, Haines discovered and reported this phenomenon called soil-water hysteresis. Hysteresis may be caused by the capillary effect, contact angle effect,

entrapped soil air, or changes in soil pore structure (Hillel, 1971). Generally, there is considerable hysteresis in the matric potential-hydraulic conductivity and matric potential-water content relationships, but little hysteresis in the water content-hydraulic conductivity relationship. Hysteresis in water content-matric potential is more pronounced in coarse-textured soils in the low-matric potential range than in finer textured soils.

In detailed field studies, Nielsen et al. (1973) found that even uniform land areas exhibit large variations in hydraulic conductivity and that measurement methods used in the field were more accurate than those required to characterize the hydraulic conductivity of an entire field because of the soil heterogeneity. They concluded that simplified methods of measuring hydraulic conductivity are sufficiently accurate to represent field conditions, considering the overall field variability. Field methods to measure soil-water properties have been developed by Davidson et al. (1969).

Three methods commonly used for relating soil core hydraulic conductivity to matric potential are (1) to represent these data in tabular form, (2) to fit the equation $K(h) = K_s e^{ah}$ developed by Philip (1968), or (3) to fit equation $K(h) = a/(h^n + b)$ developed by Gardner (1958) where K is hydraulic conductivity, h is matric potential, K_s is saturated conductivity, e is exponential function, and a, b, and n are constants related to the soil properties.

Early analyses of water movement in the soil considered either wetting or drying of the soil profile to avoid problems involving hysteresis (Green and Ampt, 1911; Kostiakov, 1932; Horton, 1940; Philip, 1957). However, numerical approximation methods utilizing high speed digital computers have enabled researchers to model soil water movement during various combinations of infiltration, redistribution, drainage, and evaporation processes. These numerical techniques have also permitted researchers to model water movement in sloping heterogeneous soil systems having variable infiltration. However, field validation of computer simulations is often frustrated by instrumentation problems and the difficulty of measuring input parameters. Extrapolation to large-scale areas must also take into consideration spatial variability of soils; this variability often overshadows hysteresis effects upon watershed scale predictions of soil water movement.

Initially, modeling studies of infiltration and subsequent redistribution were reported for soil columns by Staple (1966), Rubin (1967), and more recently by Youngs and Poulovassilis (1976). The next step, combining infiltration, redistribution, drainage and evaporation of water from soil columns, was reported by Hanks et al. (1969). Dane and Wierenga (1975) modeled the same processes in a layered soil. To account for spatial variability, Perrens and Watson (1977) developed a two-dimensional model to evaluate redistribution following infiltration. All of these researchers have accounted for the effects of hysteresis and redistribution when simulating soil water movement in situations similar to natural conditions.

The next thrust in modeling soil water infiltration was the simulation of the soil water profile during periodic water application (Klute and Heerman, 1974) and during intermittent rainfall (Bauer, 1974; James and

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TWO-PHASE FLOW THEORY AND ITS APPLICATION TO INFILTRATION

A. Klute

INTRODUCTION

Unsteady-state flow of the solution phase, as it occurs in infiltration, drainage, and various other unsaturated flow situations, is a two-phase flow process. The gas phase is also in unsteady-state flow. In most discussions of soil water flow the assumption is made that the gas-phase pressure is spatially and temporally constant, and atmospheric, due to the relatively low viscosity of the gas phase and to its (assumed) ease of escape from or entrance to the porous medium. Infiltration situations in which the gas-phase pressure is not constant nor atmospheric are easily imagined and have been demonstrated and discussed in the literature. Transport equations to account for the important features of gas-phase and liquid-phase flow have been developed. This article outlines some of the salient features of the two-phase transport equations to identify some methods of application to the infiltration process and to summarize their major characteristics.

TWO-PHASE FLOW TRANSPORT EQUATIONS

Mass Balances

The mass balance equations for the liquid phase and the air phase (subscripts w and a respectively) are (see List of Symbols for definition of symbols):

$$\frac{\partial \rho_w}{\partial t} = - \nabla \cdot \overline{f}_w + G_w \qquad (1)$$

$$\frac{\partial \rho_a}{\partial t} = - \nabla \cdot \overline{f}_a + G_a \qquad (2)$$

Assuming that $G_w = G_a = 0$, that d_w is constant, and that the total porosity ϕ is not time dependent, equations (1) and (2) may be written:

$$\frac{\partial \theta_w}{\partial t} = - \nabla \cdot \overline{Q}_w \qquad (3)$$

$$\frac{\phi \partial S_w}{\partial t} = - \nabla \cdot \overline{Q}_w \qquad (4)$$

$$\frac{\partial (d_a \theta_a)}{\partial t} = - \nabla \cdot (d_a \overline{Q}_a) \qquad (5)$$

$$\frac{\phi \partial (d_a S_a)}{\partial t} = - \nabla \cdot (d_a \overline{Q}_a) \qquad (6)$$

Flux Equations

The fluxes of the phases are usually related to their driving forces by Darcy-type expressions:

$$\overline{Q}_w = - k \frac{k_{rw}}{\mu_w} (\nabla P_w - \overline{k} d_w g)$$

$$= - \kappa_w (\nabla P_w - \overline{k} d_w g) \tag{7}$$

$$\overline{Q}_a = - k \frac{k_{ra}}{\mu_a} (\nabla P_a - \overline{k} d_a g)$$

$$= - \kappa_a (\nabla P_a - \overline{k} d_a g) \tag{8}$$

Auxiliary Relations

The saturations are connected by the relation:

$$S_w + S_z = 1 \tag{9}$$

The gas-phase density is related to the gas-phase pressure by the gas law:

$$d_a = P_a / RT \tag{10}$$

The capillary pressure:

$$P_c = P_a - P_w \tag{11}$$

The saturation - capillary pressure function:

$$S_w = S_w(P_c) \tag{12}$$

Comments

Equations (4), (6), (7), (8), (9), (10), (11) and (12) comprise a set of 8 equations in 8 unknowns: S_w, S_a, $\overline{Q}_a$, $\overline{Q}_w$, d_a, P_a, P_w, and P_c.

It is assumed that ϕ and the functions $\kappa_a(P_c)$, $\kappa_w(P_c)$ (or $\kappa_a(S_w)$, $\kappa_w(S_w)$), $P_c(S_w)$, which are presumed characteristic of the soil, are known.

Various combinations of the above cited equations are possible to eliminate explicit appearance of one or more of the unknowns and reduce the number of equations.

List of Symbols

t	time
ρ_w	mass of liquid phase per unit volume of porous medium
ρ_a	mass of gas phase per unit volume of porous medium
$\bar{f}_w$	mass flux of the liquid phase = $d_w\ Q_w$
$\bar{f}_a$	mass flux of the gas phase = $d_a\ Q_a$
$\bar{Q}_w$	volumetric flux of the liquid phase
$\bar{Q}_a$	volumetric flux of the gas phase
d_w	density of the liquid phase
d_a	density of the gas phase
G_w	source term for the solution phase; the mass of the liquid phase produced per unit time and volume of porous medium
G_a	source term for the gas phase
ϕ	total porosity
θ_w	volumetric liquid phase content; volume of liquid phase per unit volume of porous medium
θ_a	volumetric gas-phase content
S_w	the liquid-phase saturation; $= \theta_w/\phi$
S_a	the gas-phase saturation; $= \theta_a/\phi$
k	intrinsic permeability of the medium
μ_w	liquid-phase viscosity
μ_a	gas-phase viscosity
k_{rw}	relative liquid-phase permeability
k_{ra}	relative gas-phase permeability
P_w	the liquid-phase pressure
P_a	the gas-phase pressure
$\bar{k}$	unit vector in the z direction; z taken as + downward
P_c	the capillary pressure

g the acceleration constant for the prevailing gravitational force field

$\kappa_a = \frac{k\,k_{ra}}{\mu_a}$, the mobility of the air phase

$\kappa_w = \frac{k\,k_{rw}}{\mu_w}$, the mobility of the liquid phase

The Hydraulic Properties

Figures 1A and 1B illustrate the nature of the relations between the relative permeabilities, capillary pressure and saturation.

THE SOLUTION OF THE TWO-PHASE FLOW EQUATIONS

In the following, one-dimensional vertical flow in the z direction will be assumed.

Numerical Finite Difference Procedure

Phuc and Morel-Seytoux (1972) used finite difference methods to solve the set of equations:

$$\phi\frac{\partial S_w}{\partial t} = \frac{\partial}{\partial z}\left(\kappa_w\left(\frac{\partial P_a}{\partial z} - \frac{\partial P_c}{\partial z} - d_w g\right)\right) \tag{13}$$

$$\phi\frac{(1-S_w)}{RT}\frac{\partial P_a}{\partial t} = -\frac{\partial}{\partial z}(d_a Q_a) - d_a\frac{\partial Q_w}{\partial t} \tag{14}$$

$$Q_a = -\kappa_a\left(\frac{\partial P_a}{\partial z} - d_a g\right) \tag{15}$$

$$Q_w = -\kappa_w\left(\frac{\partial P_a}{\partial z} - \frac{\partial P_c}{\partial z} - d_w g\right) \tag{16}$$

$$d_a = P_a / RT \tag{17}$$

$$P_c = P_c(S_w) \tag{18}$$

The above equations are obtainable by appropriate manipulation of the basic equations in Introduction of these notes. They are a set of 6 equations in the 6 unknowns: P_a, P_c, S_w, d_a, Q_a and Q_w. Equations (13) and (14) are nonlinear partial differential equations (p.d.e.). An implicit numerical solution scheme was used on equation (14), and an explicit scheme on equation (13). The two equations were solved in an alternating step-wise fashion.

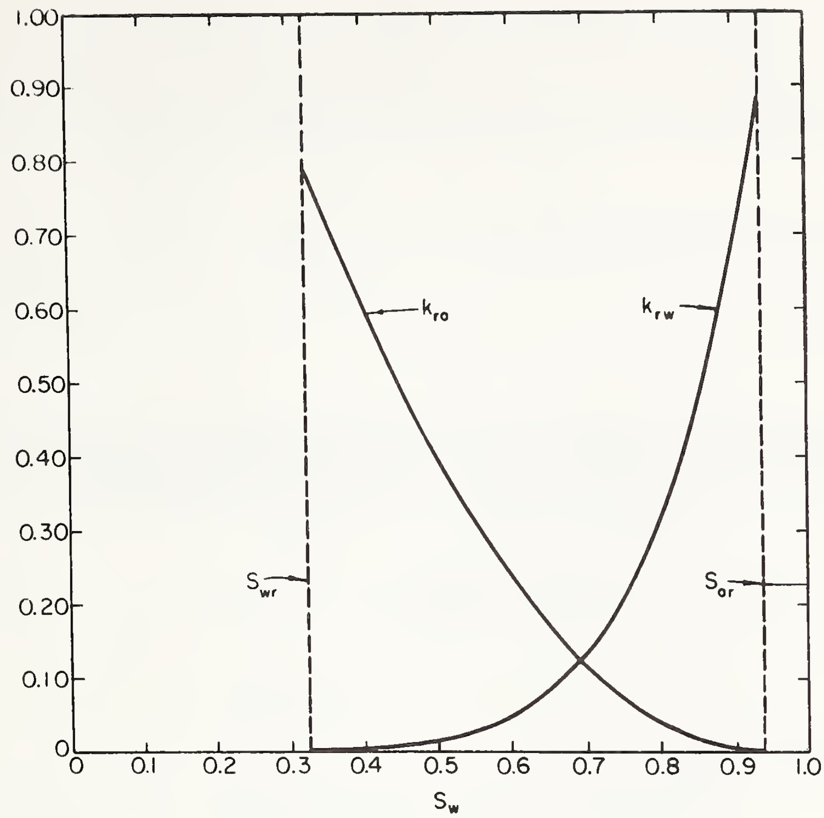

Figure 1A.--Relative permeabilities versus water saturation.

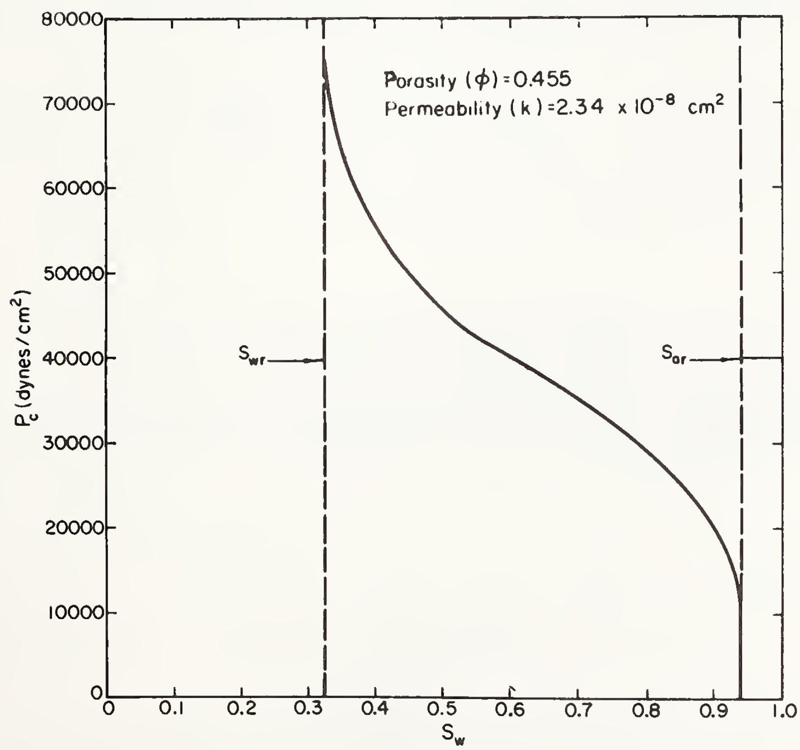

Figure 1B.--Capillary pressure versus water saturation.

In the solution methods to be described below the concepts of total velocity and fractional flow are used. The total velocity is:

$$Q = Q_a + Q_w \tag{19}$$

and the fractional flow function is:

$$F_w = \frac{Q_w}{Q} \tag{20}$$

A water saturation equation may be derived from the mass balance for the liquid phase (Eqn. (4)), the capillary pressure definition (Eq. (11)), the Darcy equations for the phases (Eqns. (7) and (8)) and Eqns. (19) and (20):

$$\phi\frac{\partial S_w}{\partial t} = -\frac{\partial}{\partial z}\left(Q\Gamma + E(S_w)\frac{\partial S_w}{\partial z}\right) \tag{21}$$

where

$$\Gamma = \frac{\kappa_w}{\Lambda}\left[1 + \frac{\kappa_a}{Q}\Delta d \ \ g\right] \tag{22}$$

$$E(S_w) = \frac{\kappa_w\kappa_a}{\Lambda}\frac{dP_c}{dS_w} \tag{23}$$

$$\Delta d = d_w - d_a \tag{24}$$

$$\Lambda = \kappa_a + \kappa_a \tag{25}$$

Equation (21) is a p.d.e. in the unknowns S_w and Q.

A second equation for the total velocity Q is obtained from the Darcy equations of the phases. The two flux equations are added and integrated with respect to z to obtain:

$$\int_{z_1}^{z_2}\frac{Q}{\Lambda}\,dz = (P_{w1} - P_{w2}) + (P_{c1} - P_{c2})$$

$$+ \int_{P_{c1}}^{P_{c2}}\frac{\kappa_w}{\Lambda}\,dP_c + g\Delta d\int_{z_1}^{z_2}\frac{\kappa_w}{\Lambda}\,dz + d_a g\,(z_2 - z_1) \tag{26}$$

Equations (21) and (26) are two equations in the two unknowns S_w and Q. Since Q is a function of z and t, and κ_a and κ_w are dependent on S_w, the function Γ depends on S_w and z and t. Since S_w is in turn a function of z and t, Γ may also be regarded as a function of S_w and t.

The Brustkern Method: In this method the capillary term in the saturation equation (21) is neglected to obtain:

$$\phi \frac{\partial S_w}{\partial t} = - \frac{\partial}{\partial z} (Q \, \Gamma) \tag{27}$$

The gas phase is assumed incompressible. Then Q is a function of t only. The total velocity equation then becomes:

$$Q(t) = \frac{(P_{a1} - P_{a2}) + g d_w \int_{z_1}^{z_2} \frac{\kappa_w}{\Lambda} \, dz + \int_{P_{c1}}^{P_{c2}} \frac{\kappa_w}{\Lambda} \, dPc}{\int_{z_1}^{z_2} \frac{dz}{\Lambda}} \tag{28}$$

In deriving (28), terms involving d_a have been neglected.

Expanding the right side of (27), recognizing the independence of Q on z, and considering Γ a function of S_w and t, the result is:

$$\phi \frac{\partial S_w}{\partial t} = - Q \, \Gamma' \frac{\partial S_w}{\partial z} \tag{29}$$

where

$$\Gamma' = \left. \frac{\partial \Gamma}{\partial S_w} \right|_t$$

An equation for the position of a given saturation as a function of time $z = z\,(S_w, t)$ may be derived from the definition of the differential of S_w, and equation (29):

$$\frac{dz}{dt} = \frac{Q}{\phi} \Gamma' \tag{30}$$

Integration of the above gives

$$z(S_w, t) = z_o + \frac{1}{\phi} \int_{t_o}^{t} \Gamma' \, Q(t) \, dt \tag{31}$$

If the time interval $t - t_o$ is sufficiently small, Q(t) may be replaced with an average value $\overline{Q}$ appropriate for the interval. Then

$$z\ (s_w,\ t) = z_o + \frac{\overline{Q}}{\phi}\ \Gamma'\ (t - t_o) \tag{32}$$

(Note: Γ' becomes a function of S_w only, under these circumstances.)

The computational procedure is as follows:

(1) Select z, and z_1 at points where P_a is known, e.g., at the soil surface and ahead of the wetting front.

(2) Calculate Q (t_o) from Eqn. (28). Use the initial condition $S_w(z_1 t_o)$ to obtain κ_w (z, t_o) and Λ (z, t_o). The integrals with respect to z in equation (28) can then be evaluated. Use P_c (S_w) in $\kappa(S_w)$ and $\kappa_a(S_w)$ to evaluate the integral with respect to P_c. Note that this integral is independent of the saturation profile shape.

(3) Use Q (t_o) as $\overline{Q}$ in Eqn. (32) to calculate the new position of each saturation after a time interval Δt.

(4) Once the new profile at time t is obtained, steps (2) and (3) are repeated to advance the solution in time.

If Q = o the fractional flow function f_o cannot be defined. In this case a new function G_w defined as:

$$G_w = \frac{\kappa_w}{\Lambda}\ \kappa_a\ \Delta d\ g \tag{33}$$

is used (Sonu and Morel-Seytoux, 1976). An equation for the velocity of propagation of a given saturation can be derived:

$$\left(\frac{dz}{dt}\right)_{S_w} = \frac{Q}{\phi}\ \frac{\partial}{\partial S_w}\ \left(\frac{\kappa_w}{\Lambda}\right) + \frac{1}{\phi}\ \frac{\partial G_w}{\partial S_w} \tag{34}$$

Equation (34) is then used in place of (30) when Q = 0.

<u>The Noblanc Procedure</u>: In this approach (Noblanc and Morel-Seytoux, 1972; Morel-Seytoux and Noblanc, 1973) the saturation equation (Eqn. (21)), with its auxillary definitions (22) - (25), is used. The capillary term is not neglected. The gas phase is assumed to be incompressible. A coordinate system ζ, with its origin moving with the front is introduced:

$$\zeta = z - v(t) \tag{35}$$

In this system the saturation equation takes the form:

$$\frac{\partial}{\partial \zeta}\ \left(\Sigma\ (S_w, t)\frac{\partial S_w}{\partial \zeta}\right) + \left(\Gamma' - \frac{\phi}{Q}\ \frac{dv}{dt}\right)\ \frac{\partial S_w}{\partial \zeta} + \frac{\phi}{Q}\ \left(\frac{\partial S_w}{\partial t}\right)_\zeta = 0 \tag{36}$$

where

$$\Sigma(S_w,t) = \frac{\kappa_a \kappa_w}{Q\ \Lambda} \frac{dP_c}{dS_w} = \frac{1}{Q} E(S_w) \tag{37}$$

$$\Gamma' = \left(\frac{\partial \Gamma}{\partial S_w}\right)_t \tag{38}$$

In the frontal region the evolution of the saturation profile is practically a pure translation. Hence the term $\left(\frac{\partial S_w}{\partial t}\right)_\zeta$ can be neglected and the saturation equation for the frontal region is

$$\frac{\partial}{\partial \zeta}\left(\Sigma \frac{\partial S_w}{\partial \zeta}\right) + \left(\Gamma - \frac{\phi}{Q}\frac{dv}{dt}\right)\frac{\partial S_w}{\partial \zeta} = 0 \tag{39}$$

In the soil surface region the evolution of the profile is one of "stretching" with time. In this region curvature of the profile is negligible. An equation for the saturation in this region is derived:

$$\frac{\partial}{\partial t}\left(\frac{\partial z}{\partial S_w}\right) = \frac{Q}{\phi}\left[\Gamma'' + \frac{1}{Q} E'' \frac{\partial S_w}{\partial z}\right] \tag{40}$$

The same integral equation for the total velocity (Eqn. (24)) that was used in the Brustkern procedure is used here.

Equations (39) (40) and (28) are solved subject to the boundary and initial conditions, the requirement that the saturations obtained from (39) and (40) must match smoothly and also that the net influx of water into the soil in a time interval Δt as calculated from the solution of (40) must equal the change of storage under the matched composite profile.

Summary of the Characteristics of the Solution Methods

1. Numerical: All terms in the flow equations are or can be retained. In principle, nonuniform media, hysteresis, time dependent boundary conditions, nonuniform initial conditions, and mixed-type boundary conditions can be considered. Air movement and compressibility are considered. This method yields, in principle, the best profile of saturation, but tends to be costly in terms of computer time. If the infiltration rate is of primary interest, the "excess" information obtained may not be desired.

The hydraulic properties of the soil, *viz.*, $\kappa_w(S_w)$, $\kappa_w(S_w)$, $P_c(S_w)$ are required for the solution.

2. Brustkern Method: Capillary terms are neglected in the saturation equation, but not in the total velocity equation. The gas phase is assumed in-

compressible in the mass balance. Compressibility of the gas phase is considered in the development of the gas-phase pressure in the confined gas "lens" between a wetting front and a water table. Numerical quadrature is used to evaluate integrals in the total velocity equation. The numerical techniques required are less costly than in the finite difference numerical method(s). The saturation profile is not very well predicted. The prediction of the infiltration rate is more realistic than that from the Richards' equation. The hydraulic properties of the soil must be known.

3. Noblanc Method: Capillary terms in the saturation equation are not neglected. The solution procedure uses the saturation equation and the total velocity equation. The procedure is more complicated than the Brustkern procedure. The gas-phase density is considered constant in the mass balance for the gas phase, but compressibility is considered in evaluation of the gas-phase pressure ahead of the wetting front. The saturation profile prediction is better than with the Brustkern procedure. The hydraulic properties of the soil must be known.

SOME RESULTS

Semi-infinite Case

Consider the classical problem of ponded water infiltration into a vertical soil column of semi-infinite depth, with a low initial water content.

Figure 2 shows the infiltration rate versus time as calculated for such a problem by the Brustkern procedure. The infiltration rate approaches a value somewhat less than the hydraulic conductivity at residual air saturation. Air counter flow causes the saturation at the surface to be somewhat less than $1-S_{ar}$.

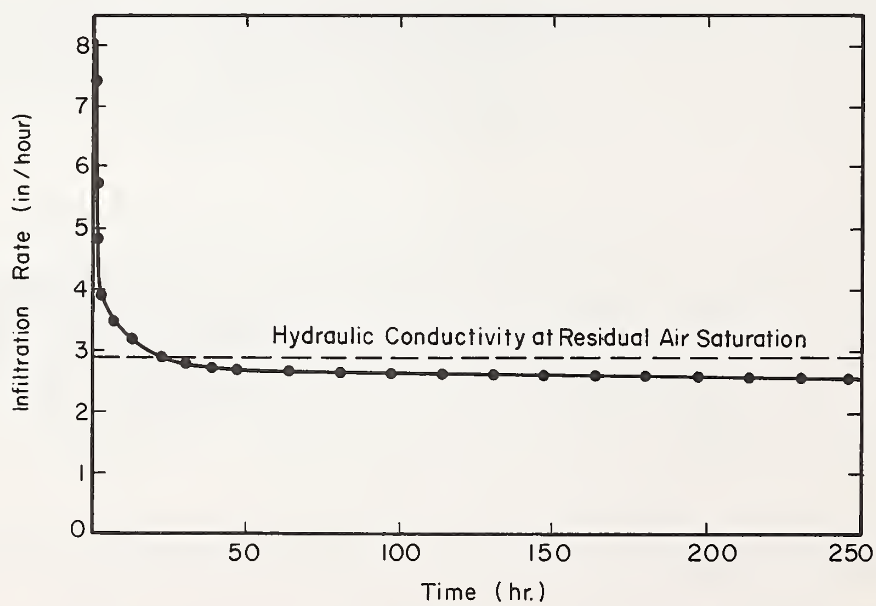

Figure 2.--Ponded water infiltration by Brustkern procedure for semi-infinite medium.

Figure 3 shows a comparison between the infiltration rate calculated from the Phuc finite difference method and the Brustkern method. At least for the selected problem the agreement is good, indicating that the latter procedure is adequate for calculation of the infiltration rate.

The saturation profiles calculated by the Brustkern method are shown in figures 4 and 5. Note the sharp, step-like front that is a result of the method of handling the multiple-valued solution in that region. Saturation profiles predicted by the Noblanc method are shown in figure 6. The profiles are somewhat "rounded off" but the fronts are very steep. The saturation at the surface decreases with time to a value less than $1 - S_{ar}$, because of the air counterflow.

Figure 7 shows air pressure profiles calculated by the Phuc method. Even in the semi-infinite case, the gas-phase pressure is greater than atmospheric in the vicinity of the wetting front and is highest in this region during the initial phases of the infiltration.

Finite Column

Consider a water table at the lower end and ponded water at the top.

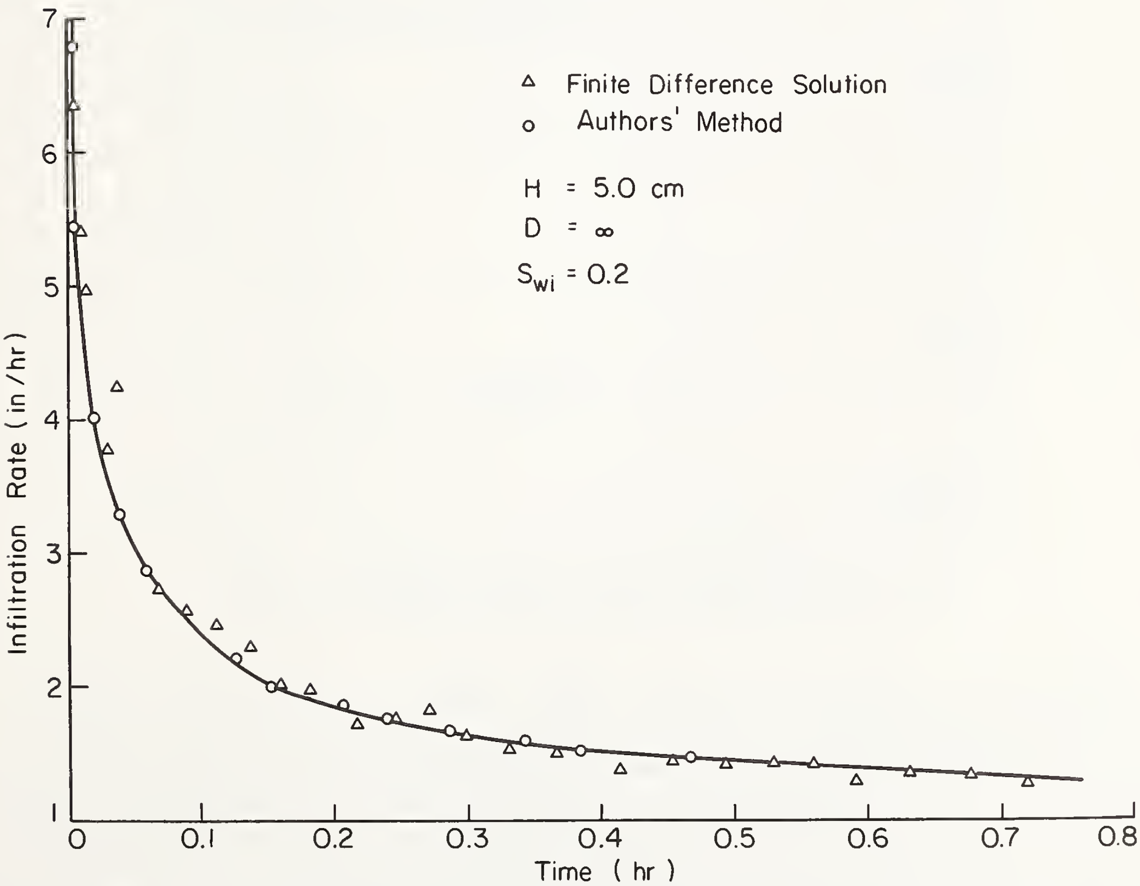

Figure 3.--Comparison of ponded infiltration solutions by Phuc and Brustkern procedures for semi-infinite medium.

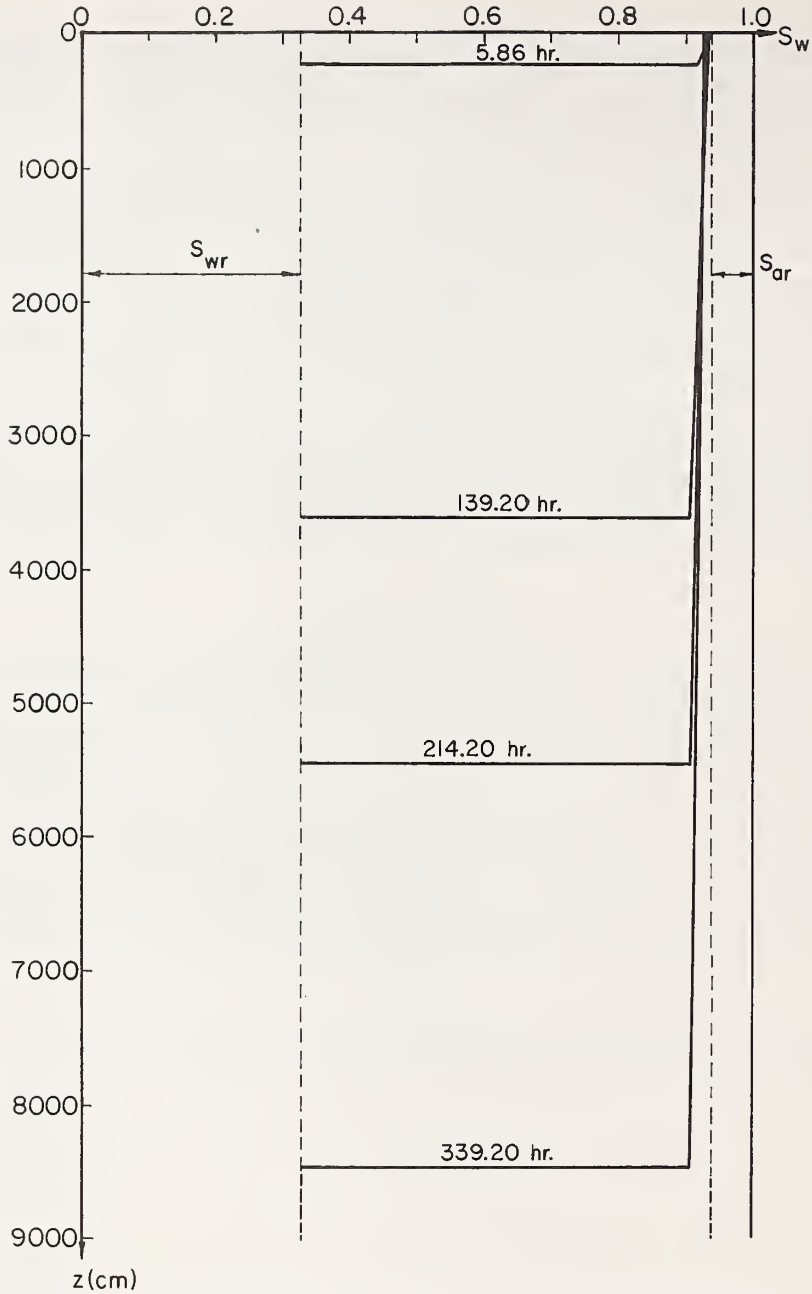

Figure 4.--Saturation profile by Brustkern method--ponded water infiltration, semi-infinite medium.

Figure 8 shows infiltration rate versus time as calculated by the Brustkern and Noblanc methods for two water table depths. Both methods predict a "dip" in the curve although not at the same time. The infiltration rate levels off at a rate significantly less than the conductivity at residual air saturation. At early times before counterflow begins, the increasing pressure ahead of the front slows the rate of infiltration. After counterflow begins the increase of pressure due to compression is not as rapid. The changes in the balance of forces with time, that is, gravity, capillary and resistive force due to pressure in the entrapped air, produce the "dip."

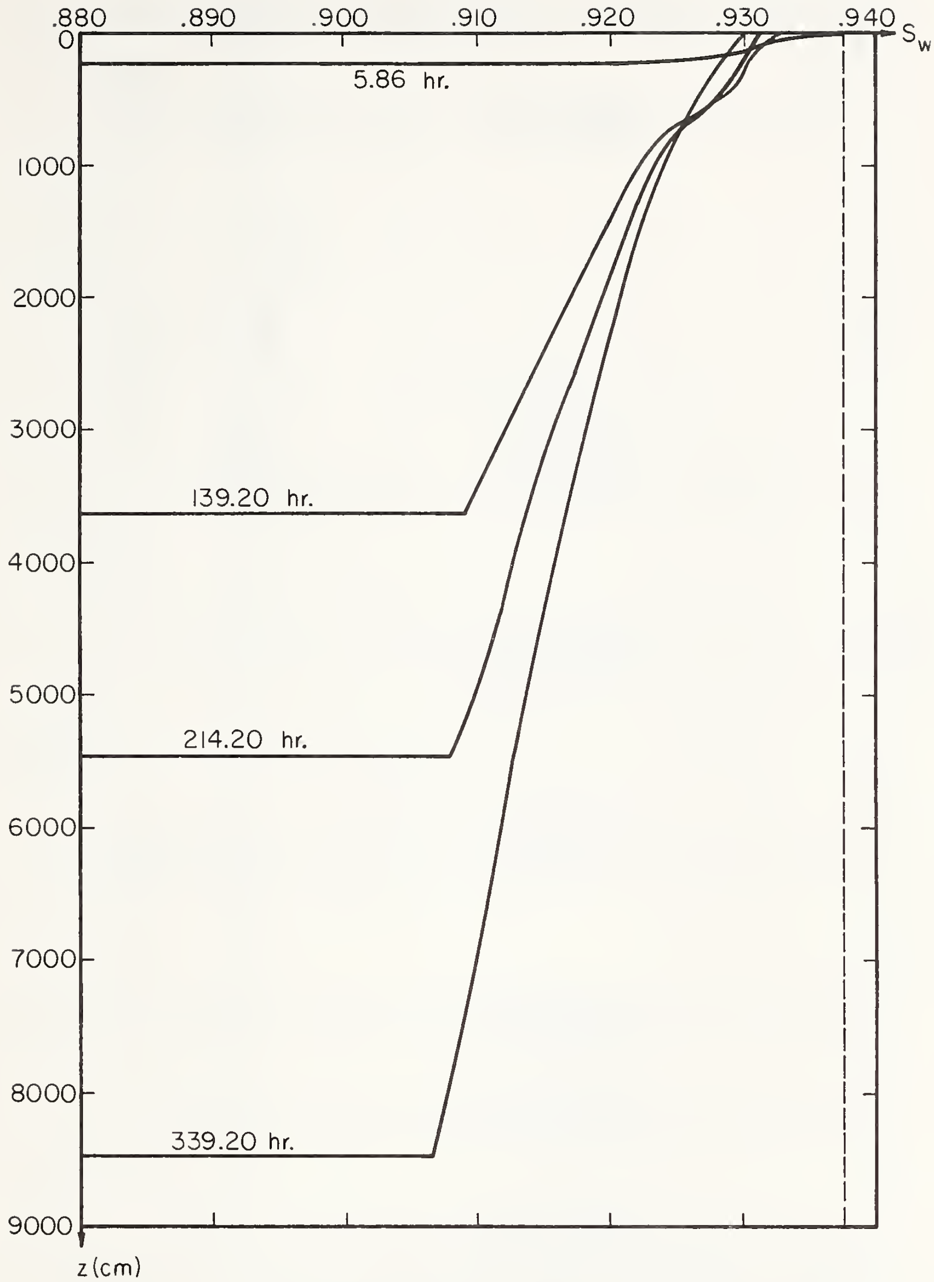

Figure 5.--Detail of figure 4.

Figures 9a and 9b show the progress of the saturation profiles with time as calculated by the Brustkern method. A lens of air is trapped between the surface ponded water and the water table, and the pressure in it builds up as infiltration proceeds. After a short time air counterflow occurs, and the saturation at the surface decreases below $1 - S_{ar}$. The front progresses downward to the water table and is then "reflected" from the water table. A small front then moves upward through the column to the surface.

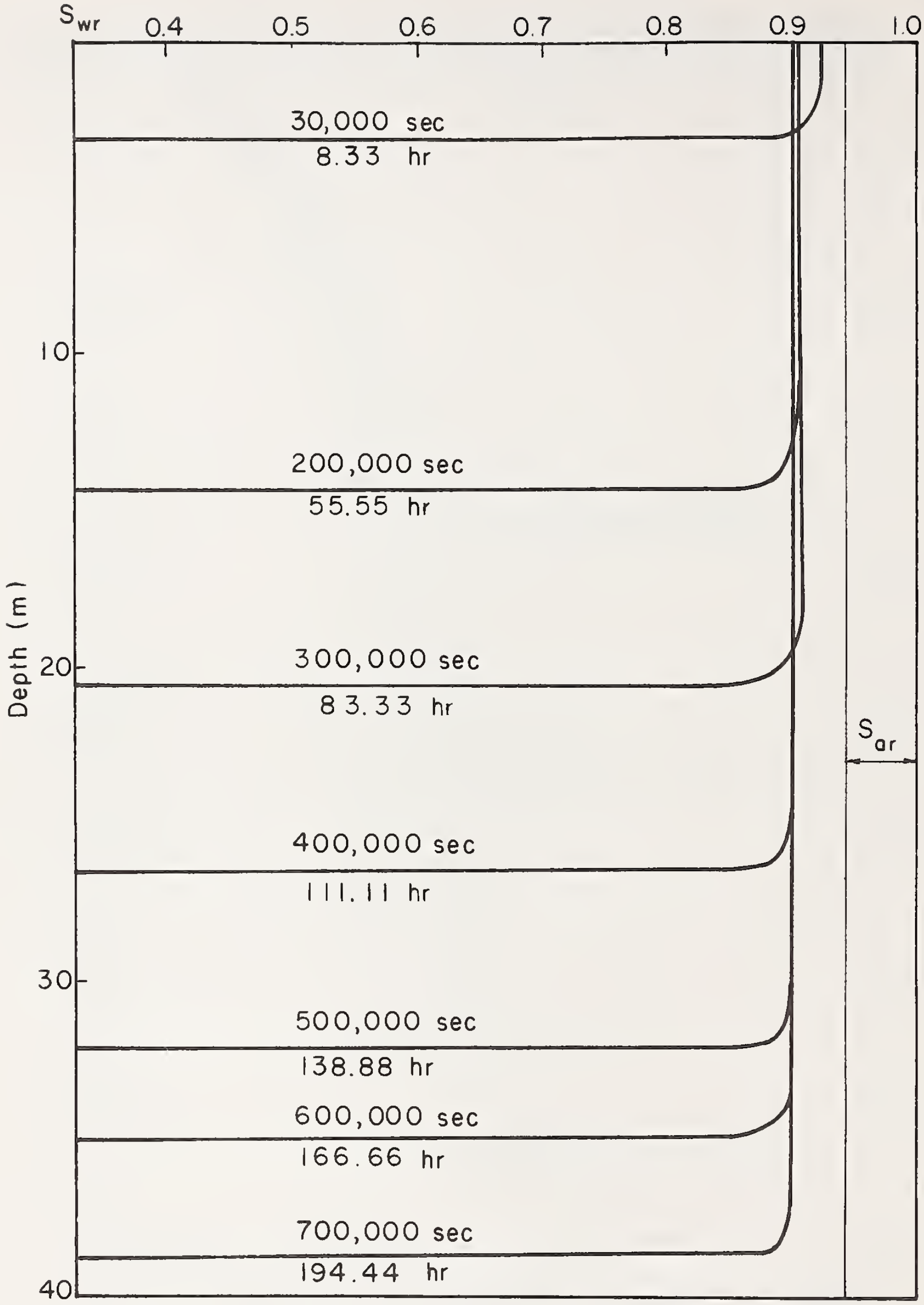

Figure 6.--Saturation profiles by Noblanc method--
ponded infiltration, semi-infinite medium.

Figures 10 through 13 show some aspects of the behavior of infiltration from ponded water into a finite column with a closed lower end as calculated by the method of Phuc.

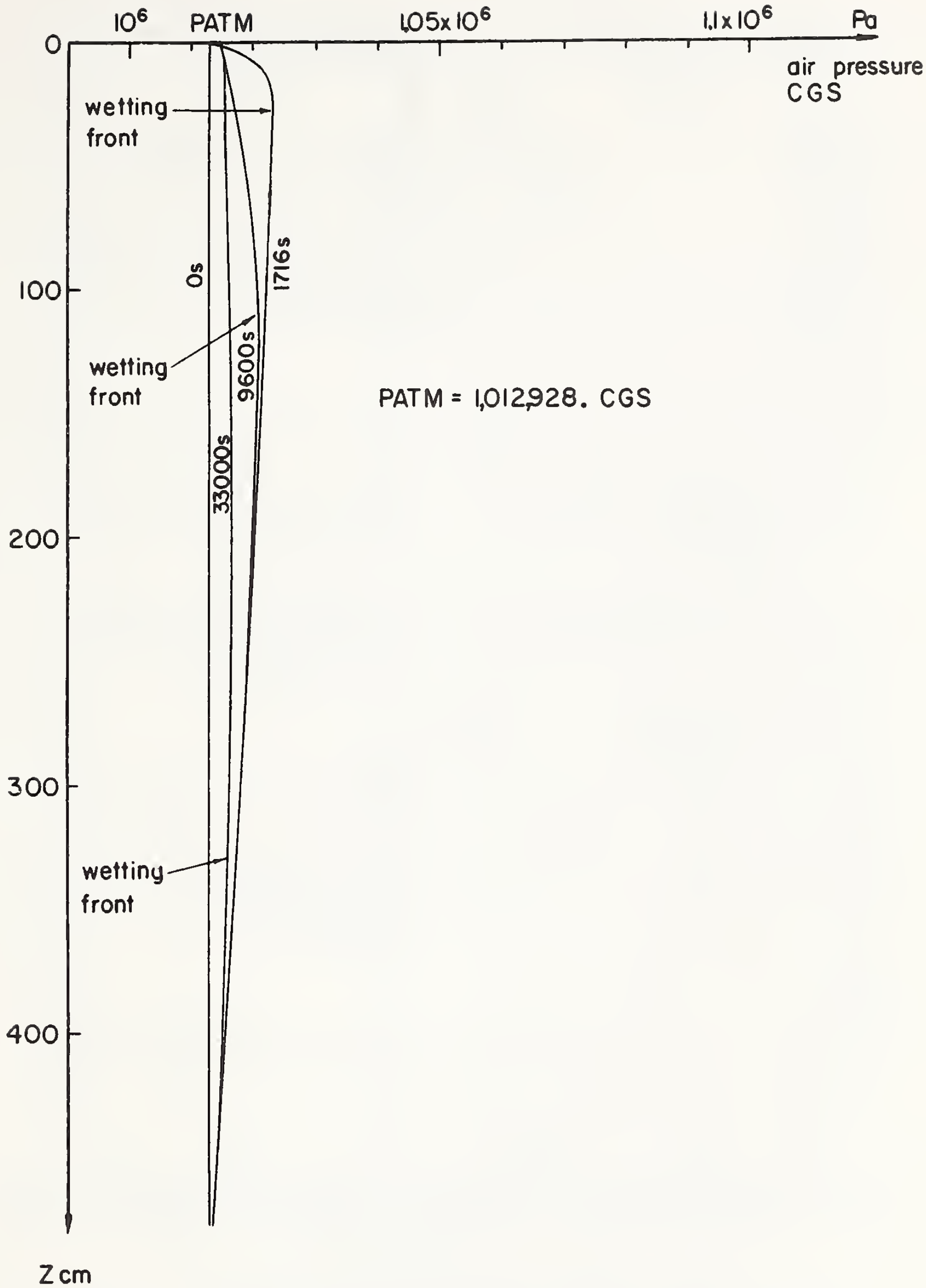

Figure 7.--Air pressure profiles by Phuc method--ponded infiltration, semi-infinite medium.

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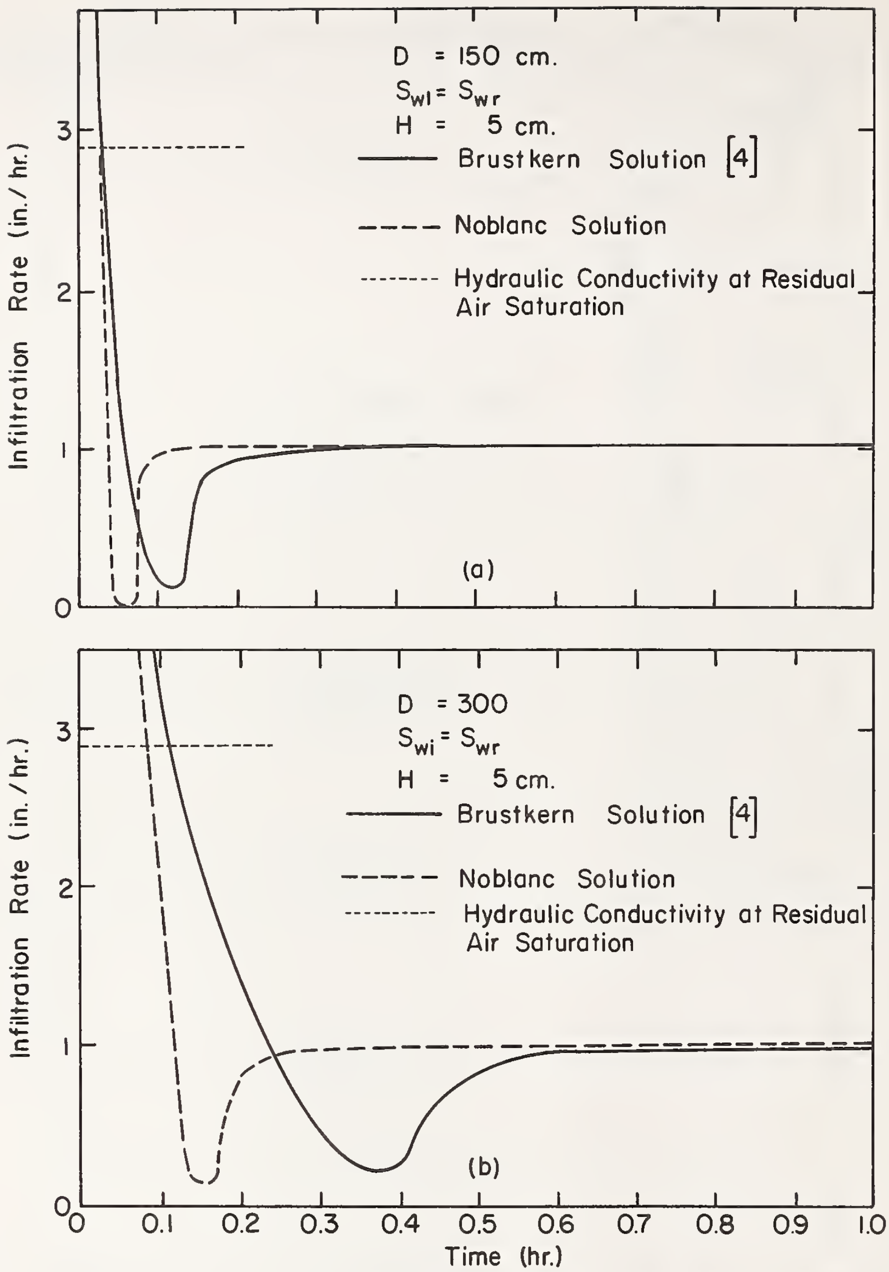

Figure 8.--Ponded water infiltration in the presence of a water table by Brustkern and Noblanc methods.

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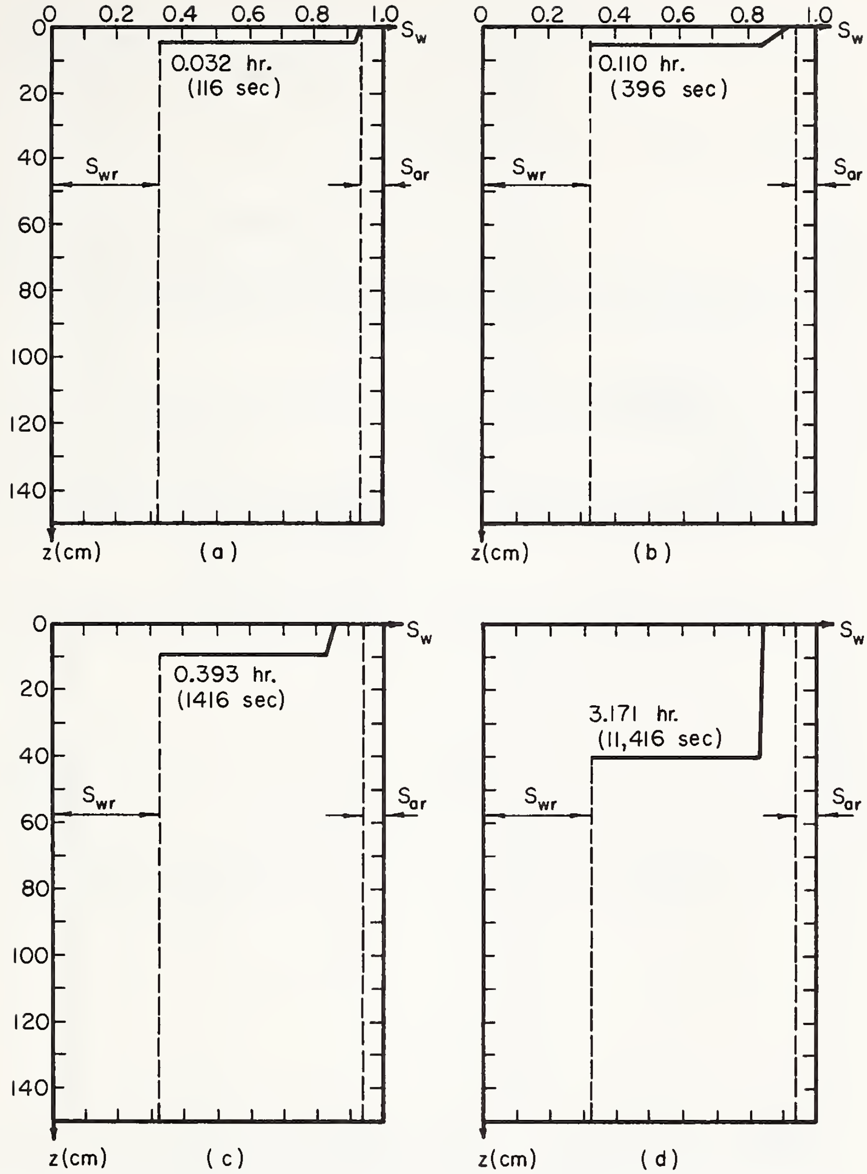

Figure 9a.--Saturation profiles by the Brustkern method--ponded infiltration and a water table.

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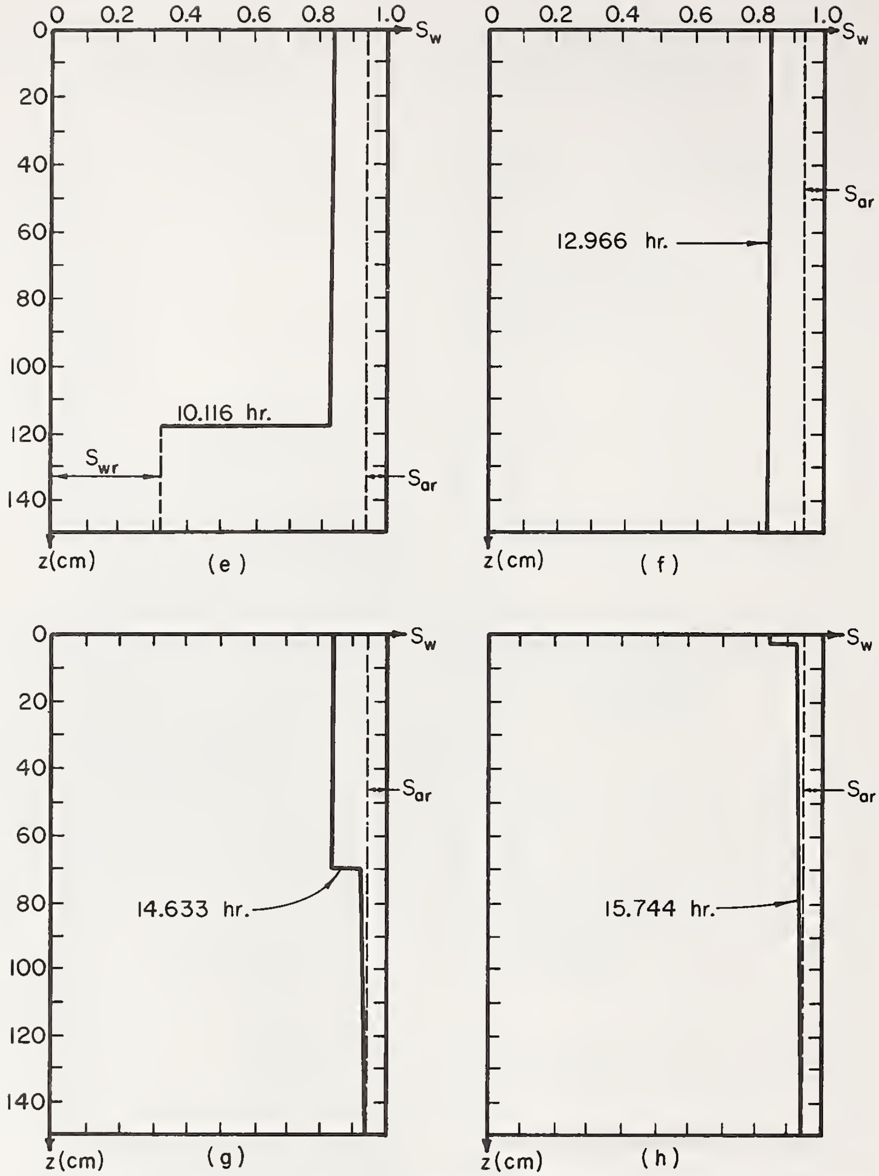

Figure 9b.--Saturation profiles by the Brustkern method--ponded infiltration and a water table.

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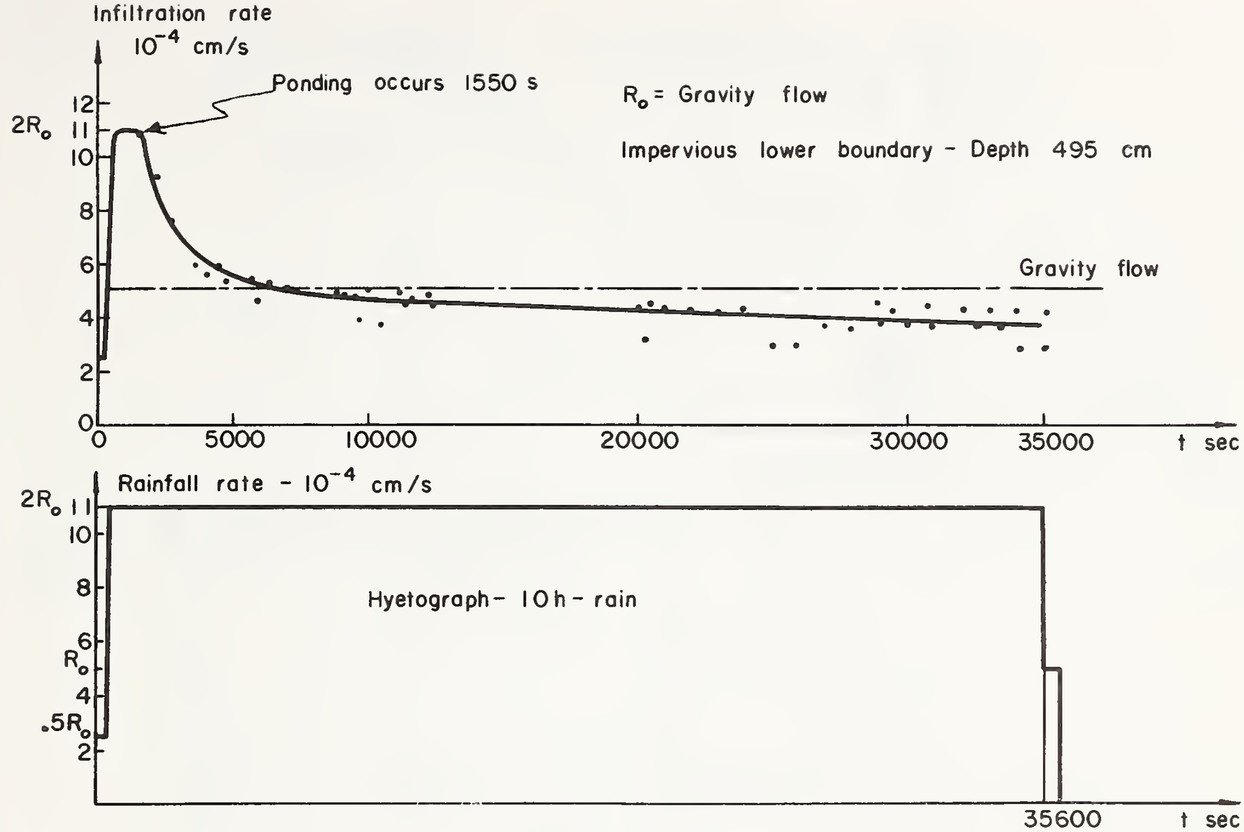

Figure 10.--Ponded water infiltration with a closed end using Phuc's method.

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Sonu, J. 1973. Water and air movement in bounded layered soil. Ph.D. Dissertation, Dept. of Civil Engineering, Colorado State University, Ft. Collins, CO.

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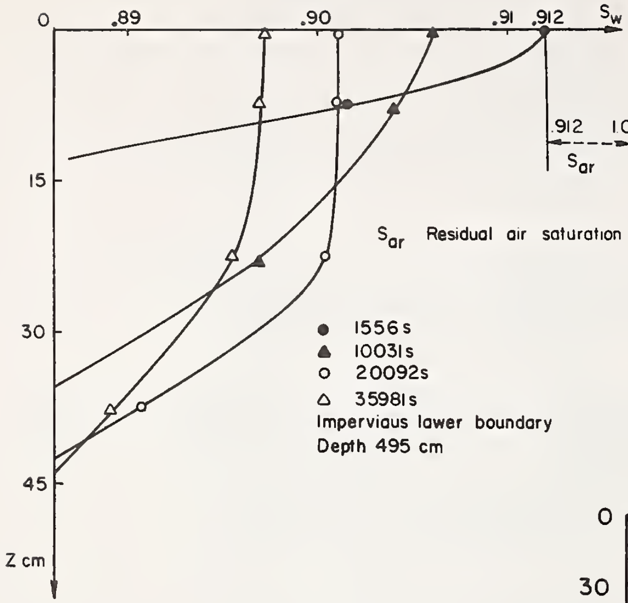
Figure 12.--Detail of figure 11.



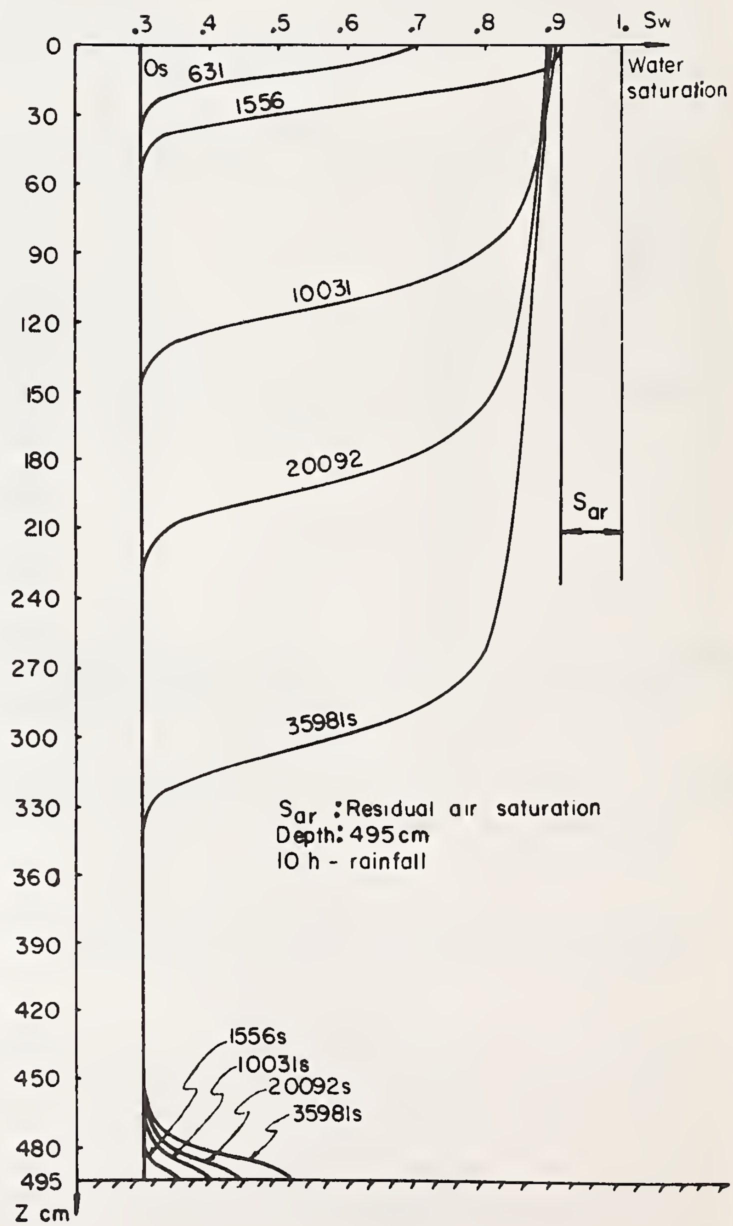


Figure 11.--Saturation profiles using Phuc's method--ponded infiltration, closed lower end.

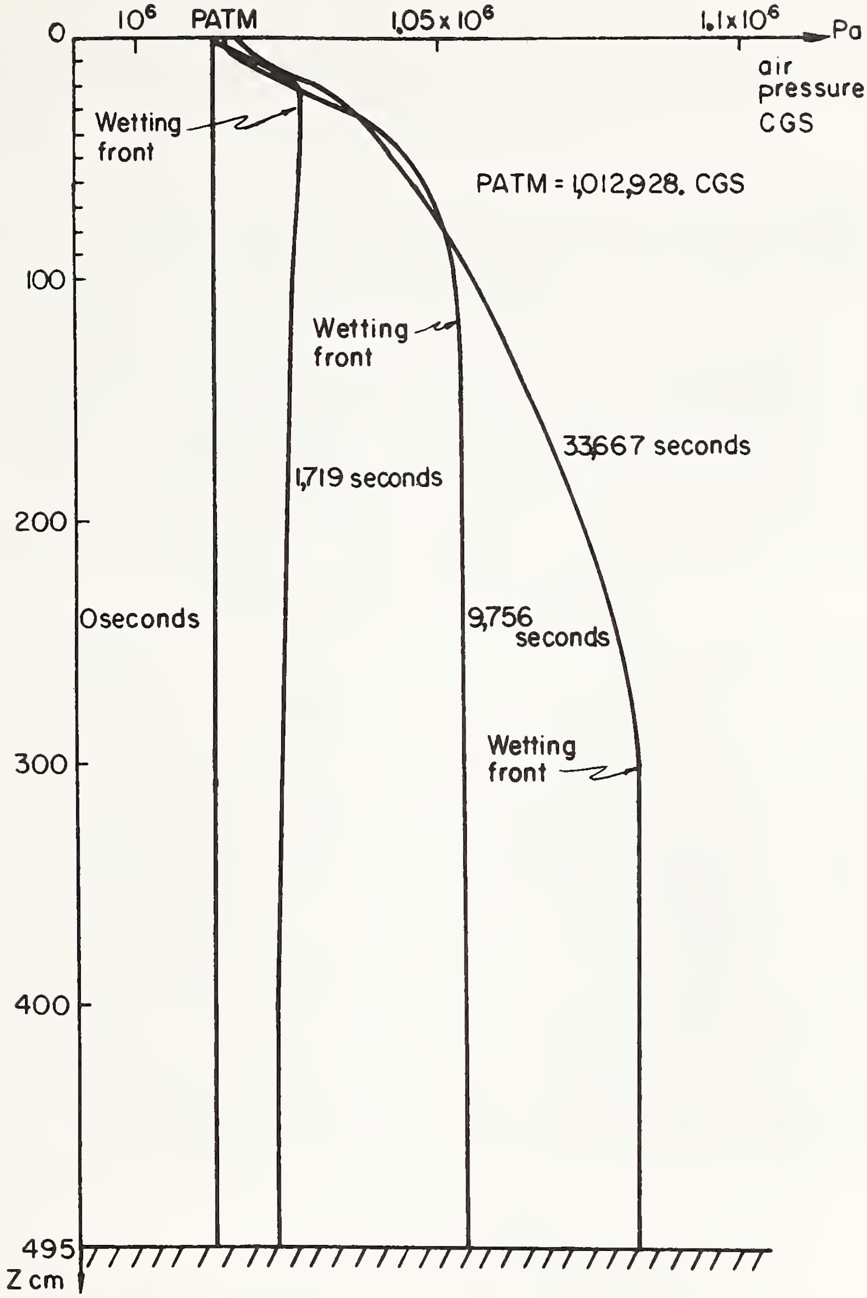


Figure 13.--Air pressure profile by method of Phuc-ponded infiltration, closed lower boundary.

SOIL CRUSTING--WHEN CRUSTS FORM AND QUANTIFYING THEIR EFFECTS

M. J. M. Römkens

The literature offers a number of articles dealing with soil crusting phenomena. This summary only concerns crust formation caused by rainfall. The initial phase or wetting phase in crust formation is usually called "surface sealing," whereas the subsequent drying phase is referred to as "crusting" in a stricter sense. The early publications dealt mostly with morphological descriptions of soil sealing, the identification of contributing factors, and a description of sequential events during seal formation. In recent years, the emphasis has been on mathematical quantification of the effect of seals and crusts on water intake. Usually, one or more simplifying assumptions are made in order to arrive at workable and acceptable solutions. Since we live today in a world of "modelers," it should not surprise anyone to find evidence of the modeler's virtues *vis-a-vis* crusting phenomena.

MORPHOLOGICAL DESCRIPTIONS

Surface seals usually are 1 to 2 mm but have been observed as thick as 1 cm. Upon drying, the seal becomes a crust, which is more compact, harder, and more brittle than the bulk soil beneath. Numerous authors have alluded to the impact of this seal on water infiltration. Some of the most frequently used references are those by McIntyre (1958), Rose (1962), Duley (1939), Ellison (1947a and b), Carnes (1934), Tackett and Pearson (1964). Generally, the events leading to crust formation can be described as follows: (1) breakdown of aggregates by slaking or raindrop impact, (2) movement of fine particles into the upper few centimeters of soil and their deposition in pores, (3) compaction of the soil surface to form a thin film, which restricts further entry of water, (4) deposition of suspended fine particles on the surface from ponded surface conditions following a rainfall event, and (5) drying of the soil surface. The degree of surface sealing and crusting depends on the hydrologic event and the antecedent and intrinsic soil characteristics. No systematic investigations have been made to relate these latter factors to well-defined and measurable parameter(s) of surface crusts.

QUANTIFICATIONS

Constant Crust Characteristics

Efforts have focused on theoretical and laboratory simulation of crust effects on infiltration into a soil overlaid by a thin crust of low conductivity. Hillel and Gardner (1969) developed the following mathematical relationship for steady infiltration through a fully developed crust into a partially desaturated soil column:

$$q = K_s^{1/n+1} \quad (h_a/R_c)^{n/n+1}$$

where q = flux, K_s = saturated hydraulic conductivity of the bulk soil, h_a is the air-entry value, R_c = crust resistance, and n is a soil characteristic.

This relationship, however, applies only when the crust resistance is sufficiently large to develop a partially desaturated bulk soil underneath the crust. Hillel and Gardner (1970) expanded their theory concerning infiltration into crusted soil to include transient situations. The relationships arrived at are:

$I \simeq s\sqrt{t}$ (Intermediate times or all times with negligible gravitational influence)

$I = K_u t + E \ln(1 + Ft)$ (large times)

where $s = \sqrt{2K_u H_f \Delta\theta}$, $E = (H_f - R_c K_u)$, and $F = \frac{K_u}{H_f \Delta\theta}$. In these relationships H_f represents the effective pressure head at the wetting front, $\Delta\theta$ = the difference in the water content in the transmission zone relative to the original moisture content, K_u is the transmission zone hydraulic conductivity, R_c is the crust resistance, and I is the cumulative infiltration. These solutions may be applicable to field situations in the absence of cultivation between rainstorms.

Transient Crust Characteristics

Infiltration into a uniform soil profile with transient crust characteristics has been described by Farrell and Larson (1972). The solutions, given in the form of integral equations, are based on a time-dependent exponential relationship of the crust resistance. With negligible influence of the gravitational gradient, the solution is found in terms of an error function. (The expressions are too cumbersome and too involved to be listed in this short outline.) In any event, the derivations are based on a three-parameter exponential relationship, S = E - B exp (- t) fitted to data points of crust resistances measured by the method of Edwards and Larson (1969). The same data as well as those published by McIntyre (1958a) were used by Ahuja and Römkens (1974) to describe rain infiltration during early stages of rain infiltration using similarity analysis. In this study, however, the basic data (hydraulic conductivities) were fitted to a power function relationship $K_c = at^{-n}$, where K_c is the crust conductivity and a and n are regression constants. Again, their analysis is based on an inadequate data base. Also, the applicability of this approach becomes inappropriate for those situations where the gravitational influence is appreciable. Recently, Niknam (1977) made a sensitivity analysis of the effect of crust formation on rain infiltration. The approach consisted of a numerical solution of the Richards' equation using linear changes with time in the hydraulic properties of the crust region as boundary conditions. A similar, but improved, analysis was made by Whisler et al. (1979). The improvement consisted of crust simulations with a refined grid technique. This technique enabled detailed observations of the transient changes in water content and hydraulic head of the crust region. These analyses demonstrated that changes in hydraulic crust conductivity have a larger impact on rain infiltration than changes in porosity or water entry values.

NEEDS

The above references clearly show a blatant absence of a reliable and realistic data base. Future studies should concentrate on the formulation of relationships in which surface sealing (as expressed by a measurable parameter, such as conductivity or resistance) can be related to some basic soil properties. Then, and only then, can a better estimate be obtained of the infiltration component in the hydrologic cycle. In those situations where sealing is of no consequence, such as in fields with a vegetative cover or in areas with favorable hydrologic conditions, the traditional infiltration equation will suffice. It should further be noted that the above references strictly focus on non-swelling soils, i.e., soils with no or little visible cracking pattern. No information of a quantitative nature was found relative to rain infiltration into the latter category of soils.

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HYDRAULIC PROPERTIES FROM PHYSICAL PROPERTIES OF POROUS MEDIA/SOILS

R. E. Smith

The problem addressed in this brief study of the current status of knowledge is the derivation of hydraulic properties needed in infiltration calculations from physical properties. There are two aspects to this relationship important to research. First, it is relevant to know how various physical or mechanical changes in soil (such as freezing, plowing, or compaction from various sources) affect infiltration. Second, it is in many cases clear that it is far easier to measure field values of physical soil properties, such as bulk density, resulting from mechanical changes in soil, than to measure relevant hydraulic properties such as conductivity, not to mention water content-tension curves. In some cases, however, measurement of physical properties necessary to characterize hydraulic properties (assuming a known inter-relation) may not be significantly easier or sufficiently definitive, as indicated below.

Elementary Concepts. We ultimately seek sufficient knowledge to be able, with a minimum of simple measurements of soil properties, to define the soil porous hydraulic media. It is assumed that we can measure bulk density, total porosity, and mechanical particle size with less time and equipment than we can measure the conductivity-water retention-capillary tension relations necessary to the hydraulic characterization of the soil.

Working backward, the capillary tension-water content relation for a soil can be used with a simple assumption of a distribution of mean pore radii to derive a water content-pore size curve: given a moisture suction H, theoretical pore radius r is

$$r = 0.149/H \tag{a}$$

(see Brutsaert, 1966) for pore water. Then the resulting water content (θ) *vs.* r relation can easily be transformed into distribution of pore volume as a function of effective radius, r . Childs (1940) discussed how weathering changes or characteristic curves may be interpreted in terms of reduction of pore size fractions. The mathematical expression of pore size distributions is well covered by Brutsaert (1966).

Pore-interaction Models. Having expressions for pore size distribution, several investigators have proposed ingenious conceptual systems for calculating conductivity curves for real or experimental soils. The general method involves calculating the probability of matching of pores of different sizes in adjacent imaginary planes (something like the matching of two infinite size pieces of swiss cheese).

Childs and Collis-George (1950) used this conceptual method, with the pore size range divided into a reasonable number of equal intervals, considering the smallest of any two interconnected pores. Millington and Quirk (1959) used pore-size intervals of equal probability to obtain a simpler expression for permeability

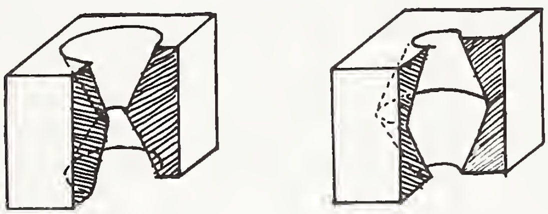
$$P_{(\varepsilon)} = \frac{\varepsilon^{4/3}}{8m^2} \sum_{i=1}^{m} r_i^2 \,(2i-1) \qquad \text{(b)}$$

where there are m classes, ε is porosity of water-filled pores.

Variations on this formula have been suggested by Green and Corey (1971), Marshall (1958), and Kunze et al. (1968) with various exponents, all experimentalists finding the need for sometimes large "matching" factors (fudge factors) to shift the curve into proper range.

Clearly this method includes arguable assumptions; i.e., flow occurs only in filled pores, and pores are characterized by a single average radius. Moreover, the matching factor is not predictable but requires an experimental determination of K at saturation.

Abstract Models. An example of another approach is that of Nakano (1976a, b) who considered the porous media divisible into interconnected elementary cubes containing contracting and expanding cylinders:



He mathematically calculated the water retention curves and pore size distribution for such a medium, given a distribution of cube sizes. Nakano did not derive theoretical permeability, and his model lacks the appeal of geometric realism.

It seems a gap exists in relating particle size distribution to hydraulic properties; or, in relating pore-size distribution and particle size distribution. Using abstract methodology similar to Nakano's, with Monte Carlo computer simulation, appears to be one likely method to obtain useful results. A study such as suggested was performed by White et al. (1970) in which particle interface geometry was used to simulate portions of the water retention curves.

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MEASUREMENT OF SOIL PHYSICAL PROPERTIES

R. F. Paetzold

Several soil physical properties influence infiltration either directly or indirectly. Five of the most important properties are examined briefly with respect to their measurement. These properties are particle size, surface area, bulk density, pore size distribution and hydraulic conductivity. The most generally accepted methods for determining these properties are summarized. Many of the standard methods are described in Agronomy Monograph 9, Methods of Soil Analysis. Other widely used methods and modifications are described in various publications such as SSIR #1 (SCS, 1972), Earth Manual (Bureau of Reclamation, 1974) and ASTM publications. For some soil physical properties, such as hydraulic conductivity, no standard methods exist.

PARTICLE SIZE DISTRIBUTION

The two standard methods for determining particle size distribution are the pipette method and the hydrometer method. While generally considered to be less accurate, the hydrometer method is adequate for most purposes (Day, 1965). In both methods, the sample is prepared by sieving the soil to remove particles greater than 2 mm in diameter. Results are reported on the less than 2 mm fraction of the soil. The sample receives whatever pretreatment necessary. Examples of optional pretreatments include: removal of organic matter, removal of carbonates, removal of gypsum and removal of siliceous cementing agents. Samples are dispersed by shaking or stirring in a sodium hexmetaphosphate or calgon solution, then wet sieved to remove the sand fraction. Particle size distribution of the sand fraction is determined by dry sieving. The remaining sample is placed in a hydrometer jar, diluted to 1 L with water and shakened or stirred to suspend the particles. The two methods differ at this point.

Hydrometer Method

A hydrometer is placed in the suspension at pre-determined times to determine the density of the suspension. Particle size distribution is calculated from these measurements. A modification which controls the depth of measurement and which also eliminates disturbance of the suspension when the hydrometer is inserted is described by Arulanandan and Smith (1971).

Pipette Method

A pipette is inserted to a specified depth (usually 10 cm) in the suspension. At predetermined times, aliquots are withdrawn, ovendried and weighed. Particle-size distribution is determined from the data.

SURFACE AREA

Several methods are available for measuring surface area, but most measurements are made using the ethylene glycol adsorption method (Mortland and Kemper, 1965). The sample is prepared and pretreated as described in the particle-size section. Additionally it is saturated with calcium by leaching or repeated centrifuging with calcium chloride.

Ethylene Glycol Method

The sample is placed in a vacuum desiccator over P_2O_5. The desiccator is evacuated with a vacuum pump for 1 h and the sample dried under the vacuum, weighed, wet with a small amount of glycol. The sample is placed in a chamber over $CaCl_2$-glycol solvate and the chamber put in a desiccator. The desiccator is again evacuated by a vacuum pump for 1 h and the sample allowed to equilibrate for about 48 h. The sample is weighed, returned to the desiccator and the process repeated until the weight is stabilized. Surface area is then calculated from the weights.

WATER RETENTION (PORE SIZE DISTRIBUTION)

There are three basic methods for determining water retention in soils. Two of these are lab methods and the other is a field method. Although other methods are available (Nagpal et al., 1972; Page, 1947; Wilkins et al., 1977; Vomocil, 1965) pore size distribution usually is calculated from water retention data.

Pressure Plate or Membrane Method

Measurement of soil water content at pressures less than 2 bars should be made on natural fabric samples (Richards, 1965). The soil sample is moistened and placed in a pressure chamber on a ceramic plate or a membrane. The pressure on the sample side of the plate or membrane is equal to the applied pressure and the pressure on the opposite side is atmospheric pressure. The pore sizes of the plate or membrane are such that below a specified pressure (bubbling pressure) they will conduct water but not air. The bubbling pressure of cellulose acetate membranes can be as high as 150 bars, and ceramic plates are available with bubbling pressures up to 15 bars. After the sample is allowed to equilibrate at the applied pressure, it is removed from the pressure chamber and analyzed for moisture content. Commonly, water contents are determined at at least two pressures, usually 1/3 and 15 bar, which are used as estimates of "field capacity" and permanent wilting point. If water content is determined at several pressures, a water retention curve can be drawn.

Hanging Water Column Method

This method usually is used only for tensions less than about 100 cm of water. The soil sample is initially saturated with water and placed on a porous plate. A tension is applied to this plate by means of a hanging water column. After equilibrating at the desired tension, the sample is removed and the moisture content determined. Veneman (1974) describes a modification of this method where the sample does not need to be removed for moisture content determination.

Field Method

This method is usually used in conjunction with other field determinations, such as hydraulic conductivity. Tensiometers are placed at desired soil depths and the soil moistened to near saturation. As the soil dries, moisture samples are taken and the tensiometers read. The moisture range of this method is from near saturation to field capacity (about 1/3 bar usually). The range can be extended to about 0.8 bar by growing plants or allowing evaporation at the site to extract water or both, but care must be taken to guard against erroneous data resulting from uneven soil water distribution.

BULK DENSITY (TOTAL POROSITY)

Although total porosity can be determined by a number of methods, the easiest and most often used method is to calculate it from the bulk density. If great accuracy is important, the soil particle density must be determined; otherwise it can be assumed to be 2.65 g/cm^3. There are a number of lab and field methods available for measuring bulk density (Campbell, 1973; Corey et al., 1971; Belcher et al., 1952; Brasher et al., 1966; Blake, 1965; SCS, 1972). The four most widely used methods are summarized.

Excavation Method

This field method is particularly useful when the soil contains coarse fragments. A quantity of soil is removed, dried and weighed. The volume of the excavation is determined by filling the hole with sand of a known bulk density or by lining the hole with a balloon and filling it with a measured amount of water. This gives the bulk density of the soil at the field moist condition.

Gamma Radiation Method

Two access tubes are installed a specific distance apart in the soil. A source is lowered to the desired depth in one tube and a detector is lowered to the same depth in the other tube. Readings are moist bulk density and must be corrected for water content so that oven dry bulk density on a field moist soil can be reported. Probes are also available that measure back scatter rather than transmission. These require only a single access tube but use a higher strength source and are not as accurate as the transmission type. Surface density meters are available that require no access tubes, but measure the density of only the upper six inches or so of the soil.

Core Method

Metal cylinders of known volume are driven or pressed into the soil, removed and the soil trimmed flush with the ends of the cylinders. The soil sample is ovendried and weighed. This gives the bulk density of the soil at the field moist condition. The samples also may be used for other measurements such as saturated hydraulic conductivity and water retention. A modification of this method (Goddard et al., 1971) utilizes a hydraulic sampling probe.

Clod Method

Clods are taken to the lab where they are dipped in a waterproofing material, commonly paraffin or liquid saran. The clods are weighed in air to obtain the moist weight and in water to obtain the volume. The moisture content of the sample is determined and the bulk density calculated. Coating with saran allows volumes to be determined at moisture contents other than the sampled field moisture content, e.g., 1/3 bar and oven dry. This in turn allows the calculation of COLE (Coefficient of Linear Extensibility), which is a measure of the shrink-swell potential of a soil. Variations of this method include weighing uncoated clods in kerosene or oil and determining volume of the clod by measuring the overflow of liquid from special containers.

HYDRAULIC CONDUCTIVITY

Many methods have been devised to measure unsaturated hydraulic conductivity (Klute, 1972; Ahuja et al., 1976; Alemi et al., 1976; Bouma et al., 1971; Dirksen, 1974; Hillel and Gardner, 1970; Nielsen et al., 1964; Rose et al., 1965; Ogata and Richards, 1957; Topp and Binns, 1976), but all suffer from one or more serious disadvantages and thus, there is no generally accepted standard method. Some of the more popular methods are summarized here. Many efforts have been made to calculate unsaturated hydraulic conductivity from more easily measured properties, such as pore size distribution (Childs and Collis-George, 1950; Marshall, 1958; Millington and Quirk, 1959; Campbell, 1974; Whisler, 1976; Jackson, 1972; Nielsen et al., 1960; Green and Corey, 1971; Jackson et al., 1965; Ghosh, 1977). Generally these methods fail unless the curves are matched with a known value. Saturated hydraulic conductivity may be determined from more or less standard methods (Boersma, 1965; Klute, 1965).

Uhland Core Method

This method measures saturated hydraulic conductivity. A metal cylinder of specific dimensions is driven or pressed into the soil at the desired depth, removed and the soil trimmed flush with the cylinder as in the core method of measuring bulk density. The core is placed on a rack or in a container and a constant head of water applied. The quantity of water passing through the soil in a specified time after equilibirium is attained is used to calculate the hydraulic conductivity. To have a large number of replicates is desirable because of the variability of results obtained from this method.

Double Tube Method

This is a field method for measuring saturated hydraulic conductivity. Two tubes, one inside the other, are inserted in the soil at the depth where the measurement is desired. Water is pumped into both tubes to saturate a zone of soil in the vicinity of the tubes. Water in the outside tube is kept at a constant level while the water level in the inside tube is allowed to drop and the rate recorded. The water levels are then brought to their original position and the water in the inside tube is allowed to drop. Simultaneously, the water level in the outside tube is kept at the same level as that in the inside tube by adjusting the water supply. Saturated hydraulic conductivity is calculated from this data.

Instantaneous Profile Method

This is a field method of measuring unsaturated hydraulic conductivity. A relatively large area (usually a plot is circular with a diameter of about 6 m) is initially saturated and covered with plastic to prevent evaporation. The plastic may be covered with soil to hold it in place and minimize thermal effects. Soil water drainage is monitored with tensiometers or a neutron soil moisture probe or both. Note that if only tensiometers or only a neutron probe is used, a moisture release curve must be provided to convert the data into a usable form so that the hydraulic conductivity can be calculated.

Crust Test Method

This is a field method of measuring unsaturated hydraulic conductivity. Saturated hydraulic conductivity may also be measured with this procedure if the crust is left off. A soil column approximately 25 cm in diameter is carved out of the soil in the horizon of interest. A metal cylinder approximately 10 cm long is placed around the column and aluminum foil is wrapped around the lower portion of the soil column, which should extend at least 30 cm to insure vertical flow. Tensiometers are inserted into the soil column through the metal ring at predetermined locations. A mixture of plaster and sand (the composition depends upon the desired water flux) is spread over the surface of the soil column and allowed to dry, thus forming a crust. A small head of water is established over the crust. When a steady-state equilibrium is attained, the flux is determined by the amount of water flowing into the soil. The tension and gradient are obtained from the tensiometers and the hydraulic conductivity calculated from Darcy's law. The procedure is repeated with different crusts, each creating a different flow rate to provide additional points on the hydraulic conductivity curve.

One-Step Outflow Method

This is a lab method for determining unsaturated hydraulic conductivity on undisturbed cores. A soil core of known geometry is placed in a pressure cell, a predetermined pressure is applied, and the rate of water outflow determined as a function of time. From these data, soil water diffusivities can be calculated and knowing the water content-tension relationship, hydraulic conductivities can be calculated.

Calculation From Water Retention Data

A computer program is used to calculate hydraulic conductivities from moisture retention values. For acceptable results a matching factor must be used, i.e., the calculated curve is shifted until the calculated hydraulic conductivity at some point, usually saturation, matches the measured value at that point. Thus, this method must be used with another so that a measured value is available. The reliability of the hydraulic conductivity curve will depend largely upon the accuracy of this measured value.

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INFILTRATION MEASUREMENTS AND SOIL HYDRAULIC CHARACTERISTICS

R. C. Sidle

MEASUREMENT OF INFILTRATION

Infiltration can be measured directly in the field with either a flooding-type or sprinkling-type of infiltrometer. If direct measurement is impractical and runoff data are available, infiltration curves can be estimated by hydrograph separation procedures.

Flooding-Type Infiltrometers

Flooding-type infiltrometers can either be single or double-ring, preferably constructed of seamless steel tubing with the inner tube having an inside diameter of about 9 in. Other sizes have been used for specialized research needs. The tubes are inserted into the soil to a depth of 12 to 24 in with a reasonably constant pressure if possible. The advantage of the double-ring system is that it provides a buffer zone which tends to eliminate lateral flow in the soils. Water is applied in a thin film with a constant head device, and intake measurements are recorded until a steady infiltration rate is observed.

Advantages of this methodology are that only a small area is needed for measurements, and it is inexpensive and relatively simple to conduct. It is ideal for small field plots where the use of a rainfall simulator would be cumbersome or impractical. Flooding type infiltrometers yield much higher infiltration rates than rainfall simulators, especially under poor or bare ground cover conditions. This is because flooding infiltrometers do not simulate rain drop impact, which leads to reduced infiltration rates. In addition, flooding measurements would tend to exaggerate the contribution of surface and subsurface macro-pores on infiltration rates. Special closed-top infiltrometers have been designed (Dixon, 1975) to correct for the effects of soil air pressure in infiltration measurements. These infiltrometers are particularly useful in cases where abundant macro-pores are present at the soil surface. This apparatus is somewhat complicated to fabricate and utilize in the field when taking extensive measurements in plot studies.

Rainfall Simulators

Rainfall simulators apply water to plots via a series of nozzles attempting to simulate the kinetic energy of raindrop impact on the soil surface. Two common models are the type F and type FA. Simulated rainfall is applied to plots at a prescribed constant rate; after constant runoff is obtained the final infiltration rate is calculated by difference. The type F infiltrometer unit sprays an area 6 x 12 ft while the type FA sprays an area 1 x 2½ ft. Recently variations of the rainfall simulator have been designed, such as a laboratory model (Romkens et al., 1975), a small portable model for rugged terrain (Munn and Huntington, 1976), and larger portable

model (Costin and Gilmour, 1970). Rainfall simulators tend to yield more realistic results than flooding-type infiltrometers; however, both types are designed to give relative values for experimental purposes.

Indirect Measurement by Hydrograph Analysis

Infiltration estimation based on hydrograph analysis is no more accurate than the precision of the hydrologic parameters measured, namely rainfall and runoff. This procedure can be utilized in areas that would not justify an extensive network of field measurements where rainfall and runoff data are available. It has the advantage of giving an integrated perspective of infiltration over relatively large areas, rather than the more isolated infiltrometer measurements. Also, watersheds or plots tested by this method have the advantage of being exposed to natural rainfall impact as well as other climatological variables. The "block method" of hydrograph analysis (Horner and Lloyd, 1940) was designed for intermediate to larger-sized watersheds where precise distribution of rainfall is not always known. The time-condensation method (Holtan, 1945), in which time is theoretically condensed to cause the mass rainfall curve to become linear, is better adapted for smaller watersheds. A method suitable for infiltration estimation on runoff plots or very small watersheds is the detention-flow-relationship method (USDA-SCS, 1956).

SOIL HYDRAULIC CHARACTERISTICS

One of the current areas of interest in soil water research that has a direct bearing on in-situ infiltration is the movement of water via inter-aggregate and macro-pores. The importance of these relatively large pores in transporting water and solutes in soil systems has been demonstrated (Aubertin, 1971; Quisenberry and Phillips, 1976; Wild, 1972; and Sidle et al., 1977).

Alterations in hydrologic processes in soils treated with organic waste material have been evaluated (Gupta et al., 1977). More extensive work in this area with a range of waste products is needed. Also, research on effects of land disturbance, such as strip mining, on infiltration and soil hydraulic properties is just beginning.

It seems that since the infiltration capacity of soil-plant complexes can be greatly manipulated by man, this area of research will need increasing attention in future years, especially as it relates to land use planning.

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INFILTROMETER USING SIMULATED RAINFALL FOR INFILTRATION RESEARCH

W. R. Hamon

INTRODUCTION

Infiltration has received considerable attention since Horton (1933) first discussed its role in the hydrologic cycle. Again, a new era of interest has evolved since infiltration functions to divide precipitation into surface and soil water components--an essential element in hydrologic modeling.

Studies dealing with infiltration prior to 1940 were surveyed in a bibliography by Davidson (1940). Another exhaustive review of infiltration literature was made by Parr and Bertrand (1959), which included references to the many types of sprinkling devices that had been employed for infiltration and erosivity measurements, and to artificial rainfall applied by drip screens and drip towers. The various approaches used in the design of rainfall simulators or sprinkling infiltrometers for an acceptable simulation of natural rainfall have been recently reviewed by Mutchler and Hermsmeier (1965).

Rainfall simulators utilize applicators based on the free fall of drops either from a tower equipped with a drop-forming device (Steinhardt and Hillel, 1966) or using a nozzle to spray water up to a certain elevation (Shachori and Seginer, 1962); other applicators feature downward-spraying nozzles, which generally have too high an application rate, although they have more satisfactory impact energy due to the downward discharge of water under pressure (Meyer and McCune, 1958). The technical problems then concern the achievement of a wide range of application rates while maintaining water drop-size distribution and kinetic energy similar to that of natural rainfall. Field studies furthermore require an instrument that is both portable and reasonably sturdy and trouble-free.

Many of the above requirements were met by the Purdue Infiltrometer developed by Bertrand and Parr (1961) and variations described by Dixon and Peterson (1964, 1968) and by Amerman et al. (1970). To overcome the disadvantage of the excessive application rates of the Purdue Infiltrometer, Morin et al. (1967) and Amerman et al. (1970) added a rotating adjustable aperture shutter to the infiltrometer which enabled them to obtain low application rates. This is essential if infiltrometers are to be used in studies of unsaturated soil water movement where infiltration rate is controlled by the water application rate.

The infiltrometer described by Bertrand and Parr (1961) falls short of the drop size and kinetic energy values of natural rainfall used by some workers as a design criterion (Meyer and McCune, 1958; Morin et al., 1967). All infiltrometers designed to date represent some compromise between idealized natural rainfall and the practical requirements of instrument design.

DESIGN PARAMETERS FOR RAINFALL SIMULATORS

In the use of simulated rainfall for studying the infiltration problem, there are several necessary characteristics of the simulator and other equipment comprising the infiltrometer system that need to be met. The most important of these are:

1. Drop-size distribution and fall velocity near those of natural rainfall at comparable intensities.

2. Intensities ranging from rather low values in the order of 0.20 iph, for studying unsaturated flow problems, to values in the order of 4.0 iph for creating ponded conditions; and even to higher rates for evaluation of surface retention.

3. Application area of sufficient size for satisfactory representation of soil, vegetation and treatment conditions.

4. Uniformity of intensity and drop characteristics over the area of application.

5. Continuous application of simulated rainfall with ability to simulate the time domain of natural rainfall intensities.

6. Raindrops should impact from a near vertical direction.

7. Constructed for satisfactory operation in sloping terrain.

8. Operation unaffected by wind.

9. Complete portability.

INFILTROMETER SYSTEM

A rainfall simulator gamma probe infiltrometer was designed[1/] to study infiltration on sagebrush rangelands as part of a program to utilize infiltration models and field data to determine hydraulic properties of soils (Jeppson et al., 1975). The design parameters for rainfall simulating equipment, as noted above, were incorporated into the system, including facilities for measuring the soil water status during infiltration. The following is a description of the system.

In order to make the rainfall simulator (figure 1) flexible enough to cover areas of various size, it was designed using a modular concept. The self-contained modules were .61 m (2 ft) by .92 m (3 ft) and utilized a two-compartment system of water and air (figure 2) with water drops formed by capillary needles that projected through an air gallery into a nozzle area in

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[1/] Conceptual design by W. R. Hamon, SEA-USDA, and mechanical design and construction by V. E. Penton, University of Idaho.

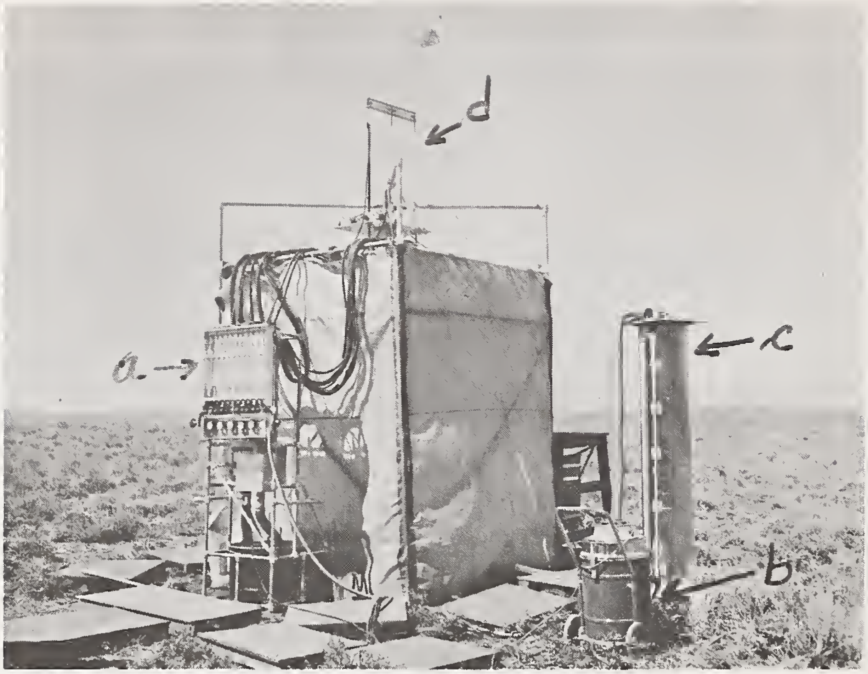

Figure 1.--Infiltrometer system showing rainfall and water-air controls (a), vacuum tank (b), runoff collector tank (c), gamma probe lift (d), and curtain enclosure for wind protection.

Figure 2.--Drop-forming modules.

the bottom plate. Each module has its own water flow measuring system and its own air pressure gage. The water flow system for each module consists of two Gilmont flow meters with metering accuracies of 2 percent of full scale. One flow meter was used to measure intensities of 0 to 3.05 cm (0 to 1.2 in) per hour and the other flow meter was used to measure intensities of 0 to 20.32 cm (0 to 8 in) per hour. The water flow is controlled by needle valves and the air flow by two air-bleed valves and an individual butterfly valve for each module. The control unit is shown in figure 3.

The system operates with water being supplied to the needles from the top compartment, forming drops on the ends of the needles. Air from the bottom compartment is forced out around the ends of the needles, forming the drop size. Changing air pressure in the bottom compartment allowed drop sizes to be varied from a mist to about 2.8 mm. Figure 4 compares the simulated drop size distribution to the drop size distribution of natural rainfall as determined by Laws and Parsons (1943) for intensities of 1.27 cm (0.5 in) per hour and 10.16 cm (4.0 in) per hour. Mean drop size of natural rainfall can be duplicated with the simulator; however, the simulated distribution is much narrower than the natural rainfall distribution. The system was calibrated such that, for a specific intensity, a certain air pressure was needed to reproduce the average drop size corresponding to that intensity.

To cover a range of intensities between 0.25 cm (0.1 in) per hour and 20.32 cm (8 in) per hour, it was necessary to use two sets of modules with two different needle sizes. One set of 0.041-cm (0.016-in) diameter needles was used for simulating intensities from 0.38 cm to 5.08 cm (0.15 to 2 in) per hour, and another set of 0.068-cm (0.027-in) diameter needles was used to simulate intensities from 5.08 to 20.32 cm (2 to 8 in) per hour. In order to obtain the high intensities and a good rainfall distribution, it was necessary to use a 7.62 cm (3 in) needle spacing. For the 0.61 m by .92 m (2 ft by 3 ft) module, there is a total of 96 needles. Six modules were used to obtain an application over a 1.83 m by 1.83 m (6 ft by 6 ft) area. Distribution tests indicated that mean rainfall had approximately a 3 percent error with a standard deviation of 30 percent. The lower intensities had the smaller average errors; however, they had the larger variation.

The rainfall simulator was designed to be 2.032 m (8 ft) off the ground. This was considered to be the most practical and still produce satisfactory kinetic energy value. Figure 5 compares the kinetic energy of natural rainfall to the simulated rainfall at intensities of 1.27, 2.54, and 10.16 cm (0.5, 1.0, and 4 in) per hour. The kinetic energies were calculated using the method developed by Wischmeier and Smith (1958). The kinetic energy produced with the simulator may be somewhat higher than that shown in figure 5 because of an initial acceleration due to the air blowing by the needles. The difference is probably small. As seen in figure 5, the kinetic energy of the simulated rain is approximately 83 percent of the kinetic energy of natural rainfall with the best reproduction of kinetic energy occurring at about 1 in per hour intensity.

The module support frame was constructed using 3.18-cm (1¼-in) aluminum pipe connected with scaffold fittings. The legs had screw adjustments for leveling the modules on slopes up to 100 percent. The frame can be dismantled into two sides plus six joining sections and the top crossbars. Assembly and disassembly of the frame and modules takes two men about 2½ hours.

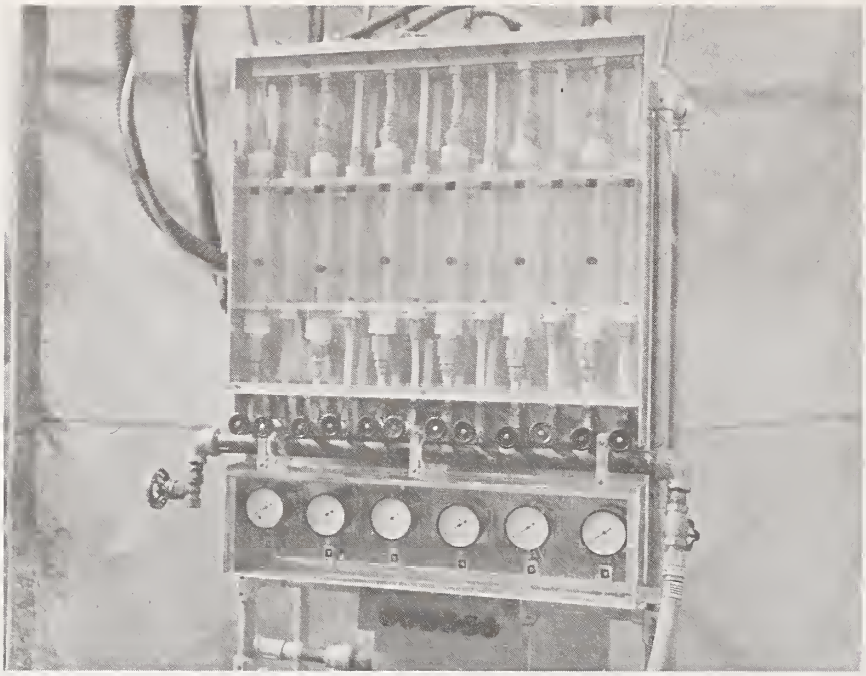

Figure 3.--Control unit, containing flow meters (upper section) and air pressure gages and needle valves (lower section), for drop-forming modules.

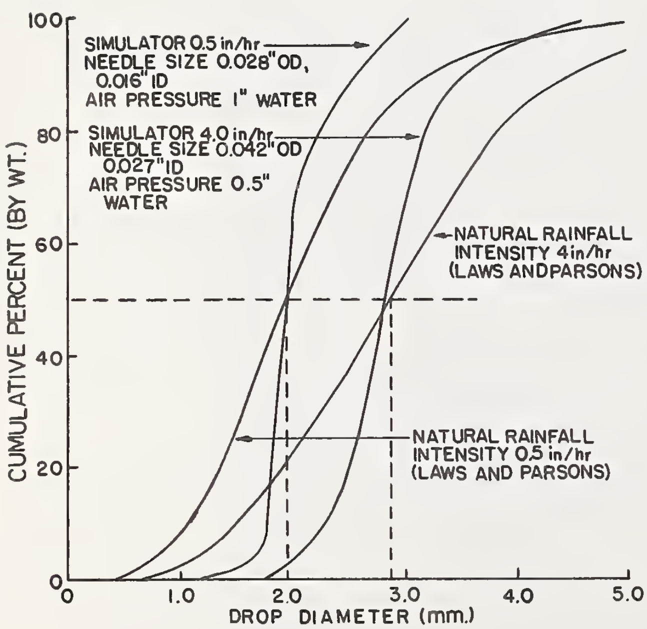

Figure 4.--Distribution of drop diameters for simulated and natural rainfall.

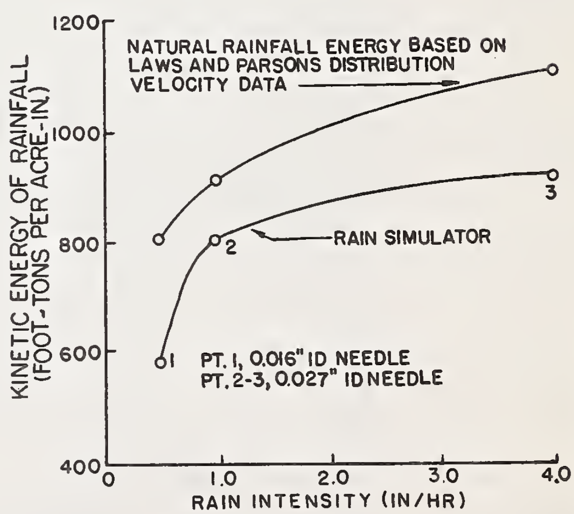

Figure 5.--Kinetic energy of natural and simulated rainfall.

To monitor the water movement in the soil, a Troxler Model 2376 two-probe gamma density gage was used. The density gage was operated remotely by a pulley and drive mechanism on the top of the rainfall simulator. Access tubes, located 30.48 cm (12 in) apart, extend through the center of the module array downward into the soil (figure 6.) The control system makes it possible to obtain density (water content) measurements and to trace the position of the "wetting front" during rainfall.

To collect surface runoff, a three-sided frame is placed around the test plot. The metal frame is driven 30.48 cm (12 in) below the ground surface and 15.24 cm (6 in) of the frame forms a border above the surface. On the open downslope side, a wooden cutoff wall, the top edge shaped to conform with the soil surface, was placed 30.48 cm (12 in) into the ground and the runoff collected in an attached trough (figure 6). Runoff is transferred from the trough to a tank by a vacuum system and measured with a water stage recorder. A fiber reinforced, plastic curtain, figure 1, is used to enshroud the rainfall simulator for protection from the wind.

The rainfall simulator gamma probe infiltrometer system as described may be used effectively to obtain the necessary data, by including the capillary pressure obtained during the infiltration tests to fully describe the infiltration process. Both "capillary flow" and "gravity flow" can be examined by using the wide range of application rates. Operation by fixed time intervals using varying application rates offers an opportunity to evaluate the "instantaneous" retention of a particular site. Finally, numerical solutions may be fitted to the field data to define the hydraulic properties of the soil.

Figure 6.--Runoff plot showing access tubes for gamma and neutron probes and runoff collection trough.

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INFILTRATION BY HYDROGRAPH ANALYSIS

C. W. Richardson

The measurement and analysis of surface runoff hydrographs provide a means for measuring infiltration under field conditions. Infiltration measurement by hydrograph analysis permits incorporation of many of the spatial variabilities that exist on a watershed. Incorporation of spatial variability has distinct advantages if the purpose of infiltration measurement is to enable prediction of surface runoff.

Watershed flow data have been used to delineate areas contributing to surface runoff as well as to define infiltration parameters. Hills (1971) used fluorescent dyes and hydrograph measurement to measure infiltration variability within an area. Measurement of overland flow from a network of plots provided a measurement of time and space variation of infiltration (Selby, 1973). Sprinkling devices are often used with small plots to measure infiltration with a variety of catchment conditions (Costin and Gilmour, 1970). Use of this device requires analysis of the resulting hydrographs to infer infiltration. The basic equation used to determine infiltration from runoff measurements is

$$F = P - Q - D_a - V_d$$

where F is cumulative infiltration; P and Q are measured rainfall and runoff, respectively; and D_a and V_d are surface detention and surface depression storages that must be estimated (Musgrave and Holtan 1965). By analyzing hydrographs at different times, solutions may be obtained for the infiltration rate and time variation of infiltration.

Musgrave and Holtan (1965) identified three basic principles that have been used to estimate infiltration from runoff hydrographs. The three methods are the detention-flow-relationship method, the time-condensation method, and the block method.

The detention-flow-relationship method is frequently used to analyze hydrographs from sprinkler-type infiltrometer plots. Sharp and Holtan (1940) adapted the method for analyzing natural hydrographs from small homogeneous watersheds. Whether analyzing hydrographs from sprinkler-type infiltrometers or small watersheds, the procedure is basically graphical. The P and Q curves are plotted for a runoff event. The P-Q curve is determined by graphical subtraction. The D_a curve is determined by trial and error procedures. A relationship is then established between D_a at a given time and the rate of surface runoff. The cumulative infiltration curve is then estimated by subtracting D_a from the P-Q curve.

The time-condensation method is an attempt to eliminate variations in rainfall by theoretically condensing time (Holtan, 1945). Time is condensed in a manner to cause the cumulative rainfall curve to become a straight line. The same time condensations are applied to the cumulative runoff curve. The theory is that, if the rainfall rate were truly constant, the curve of runoff plus detention would be either a straight line or show a smooth upward curvature approaching the slope of rainfall as an upper limit. The time-condensed cumulative rainfall and runoff curves are used with a graphical technique to estimate retention and infiltration curves.

The block method was developed by Horner and Lloyd (1940) and Sherman (1940). The block method also utilizes graphical techniques but is less detailed and laborious than the other two methods. The block method is generally adequate on larger watersheds where the time distribution of rainfall cannot be well described. To derive an infiltration curve, the method requires that there be a multi-peaked hydrograph since an average infiltration rate is computed for each burst of rainfall that produces a hydrograph peak.

In more recent years Snyder (1971) proposed a watershed retention function for estimating the rate of water retention on a watershed during a rainfall event. The function was intended to describe total watershed retention including infiltration, interception, detention and depression storages, and other factors. Storm rainfall and runoff data are used to compute watershed retention rates during the storm. The retention function parameters are optimized by fitting the function to the computed retention rates.

Infiltration obtained by hydrograph analysis is valuable because the integrated infiltration behavior of a watershed may be determined during natural rainfall events. Such an approach may be valuable when simulating the response of a watershed to rainfall. The methods that are presently available for estimating infiltration from hydrographs are laborious and do not lend themselves to computer solution. There is a need for the development of computer-oriented solutions for determining infiltration from hydrographs.

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PLANT CHARACTERISTIC EFFECTS ON INFILTRATION

K. E. Saxton

The effects of plants, their residues, and required tillage have largely been neglected in the history of infiltration research and predictions. This is exemplified by the bibliography on infiltration compiled by an ASAE committee in which fewer than 10 articles out of 485 specifically were concerned with plant effects (ASAE, 1964). Furthermore, neither Musgrave and Holtan (1964) nor Philip (1969), as two prominent examples, give any specific attention to plant-related influences. Yet, it is obvious and conceded by all hydrologists that the infiltration rate at any given time is largely affected by the plant through the effects of soil surface protection, stem penetration, root density, and required tillage--to name only a few. With this recognition, then, let's insure that dynamic plant effects are fully considered in the research plan to achieve predictable infiltration rates on agricultural landscapes.

We must recognize the dynamic nature of the plant, particularly on agricultural areas where a new crop is usually established every year. Canopies and root systems progress from nothing to nearly full soil cover, maintain that stance until maturity and harvest bring about senesence, decline, and later decay. The ensuing residues both above and below the soil surfaces continue to play a significant role.

Before discussing the instrumentation and techniques for assessing plant characteristic effects on infiltration, I feel it necessary to first consider some of the possible needs and measurements we can now visualize as being required. As a method of segmenting the plant effects, let's consider separately the effects of the above-ground portion (the canopy), the stem and crown located in and adjacent to the zone of infiltration, and then the plant roots.

CANOPY

The plant portion above ground will affect infiltration by (1) absorbing rainfall impact which will reduce puddling, sealing, and crusting, (2) deliver the precipitation to the soil surface in a redistributed pattern, different drop size, and different energy levels, (3) alter the drying rate of the soil surface, (4) etc. Plant canopy measurements to characterize these effects must describe the plant anatomy in some detail. Plant scientists, of course, have studied these forms and one finds related books under the headings of plant anatomy, plant morphogenesis, plant growth, plant physiology, etc. Examples are Sinnott (1960), Evans (1972), and Black and Edelman (1970). The text by Thornley (1976) is a particularly good review on developing mathematical models of plants. Similarly, there has been a surge in recent years of plant models by agricultural scientists. Although the purpose of most of these is crop production, their techniques may well be applicable to eventual predictions for hydrologic models.

Measurement techniques:

1. Soil Cover — -aerial photos
   -radiation penetration

2. Leaf Area Indexes (LAI) -ratio of total leaf area to associated land area
   -leaf area measurements: grid area, area meters
3. General Anatomy -general forms and shapes
   -growth patterns and interactions
4. Precipitation Interaction
   -catch cans for distribution
   -drop size and energy by flour pans, etc.
   -stem flow measurement by band diversions
   -drip lines by soil patterns, etc.
   -snow drifting and melt rates
   -soil freezing by temperature and resistance block studies

STEM

The stem penetration of the soil surface undoubtedly has some effect on infiltration, but the magnitude is difficult to even estimate. Certainly as we contrast simple stem crops, like corn and soybeans, to multi-stem or dense stem numbers of wheat and grasses, there must be a significant difference. Whether the effect is due to stems, crowns, or roots at the soil surface will be hard to assess. The plant stems and roots alter the soil they contact by growth pressures, shrink-swell (Klepper et al., 1971), and wind movement. These may or may not be significant.

Measurement techniques:

1. Stem Numbers -direct count
   -pin sampling
   -photo of clipped plot
   -resin impregnation of clipped plot
2. Stem Diameters -direct measurement at selected heights
   -photogrammetric

ROOTS

Crop roots will influence infiltration primarily through their effect on soil water flow characteristics. It is difficult to quantify roots and more difficult to assess their effect. But they are an important part of the dynamic changes within agricultural soils and must be considered. Böhm et al. (1977) list 5 techniques for measuring plant root density and development. The description of roots is complex as noted in Whittington (1968) or Larson (1974) and exemplified by the results of Taylor et al. (1970).

Measurement techniques:

1. Root Density -soil water depletion
   -framed monolith and pinboard
   -core sampling
   -mini-rhizatron
   -trench profile

2. Root and Channels -soil cross-sections
-soil profiles
-dyes and tracers

RESIDUE

Crop residue is a special case of the crop parameters just discussed. The same measurements and characterizations should apply, but obviously the effects will be slightly to drastically changed as the residue is manipulated by tillage and as the decay process ensues. The decline and decay of the plant crowns and roots also must be considered. Mannering and Meyer (1963) report some typical results of residue mulch.

Measurement techniques: -same as other plant characteristics

TILLAGE

Although tillage is not directly a part of plant characteristics, it is closely related and is another highly influential area of infiltration predictions that has received too little attention. There have been a number of studies conducted and reported (Allmaras et al., 1966; Burwell et al., 1966, 1968, 1969; Edwards, 1967) but the effects are not yet consistent and understood, and hydrologists have not introduced such factors into their infiltration prediction equations.

Measurement techniques:

1. Surface Configuration -roughness by pin drop
-random and aligned roughness
2. Soil Parameters -density
-cloddiness

MICRO-ORGANISMS

There are any number of micro-flora and micro-fauna at or near the soil surface that must influence the action of water and the action by water. What the magnitude of these effects are and how to measure and characterize these causative factors may be beyond our scope. But if they do have a significant effect, then we should engage someone with knowledge in this area.

SUMMARY

The effect of plants on the infiltration process has not had much scientific attention, yet we acknowledge that plants often have a significant effect on the potential and actual infiltration that occurs. Research to characterize plants and their effects on infiltration will be difficult and initial results likely will be generalizations and relative magnitudes. We can be gratified that much related study of plants has preceded, and others have tackled similar plant-related questions. A good example is the book by Monteith (1976) in which he reports results of micro-meteorologists to define and characterize the interaction of plants with several of the major micrometeorologic variables. Each chapter concerns a specific crop, or class of

crop, and presents results of radiation, aerodynamic transfer processes, heat and water balance, and carbon dioxide exchange. Perhaps a similar treatise describing crops and infiltration variables could be a goal of hydrologic research.

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INFILTRATION EFFECTS OF SOIL SURFACE CONDITIONS

R. M. Dixon

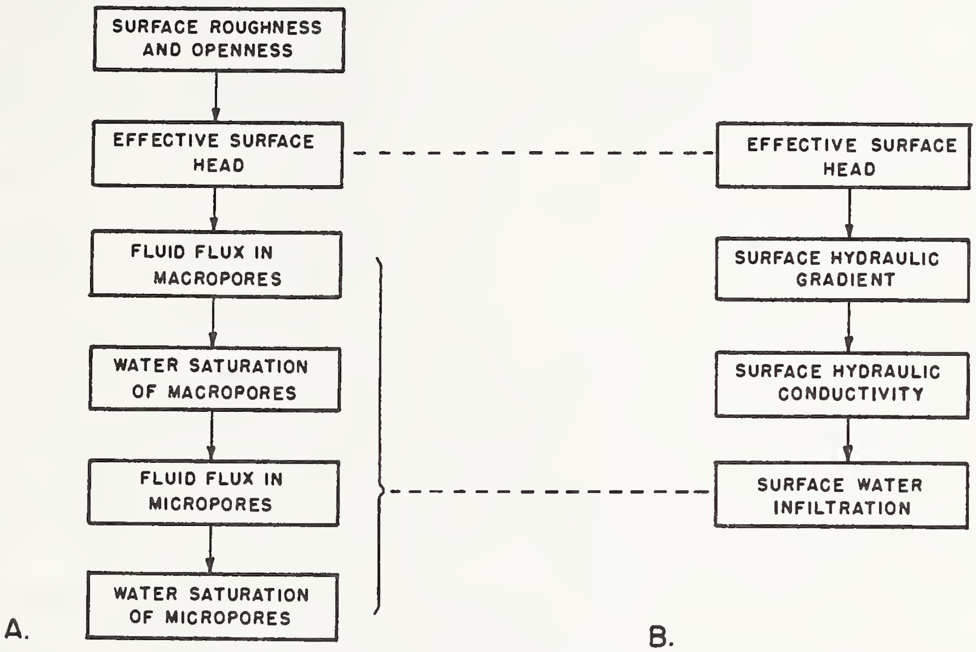
Infiltration literature contains contrasting views on the physical mechanisms controlling water infiltration into soils (Swartzendruber and Hillel, 1973). Field experimentalists such as Duley and Kelly (1939), Horton (1940), Holtan (1961), and Dixon (1966) have argued that infiltration is controlled at the soil surface, whereas theorists (Philip, 1969; Bear, 1972) have maintained that infiltration is controlled by measurable hydraulic characteristics of the soil profile. Dixon (1977) has noted that these contrasting views are not contradictory but rather are complementary. Furthermore, the surface control concepts represent valuable extensions of classical Darcy-based infiltration theory. Physical properties of the soil surface can control the transmission characteristics of the soil profile, and soil profile conditions often manifest themselves at the soil surface. The view held by Childs (1969) that infiltration is a function of hydraulic conductivity and hydraulic gradient at the immediate soil surface also seems to reconcile the contrasting views about infiltration control.

The historical development of these contrasting views is understandable, since theorists have largely neglected the infiltration role of surface conditions through their simplifying assumptions. Laboratory soils used in testing this theory commonly possess unrealistic pore space geometries, unrealistic initial conditions, and unrealistic upper and lower boundary conditions. Although such experiments have, at times, verified theory, they have contributed less than might be expected to the understanding of natural infiltration processes because the laboratory soil column models field soils very poorly. Unfortunately, the physical significance of Darcy-based infiltration theory is limited to highly idealized laboratory soils wherein the "soil surface" is usually a stable, horizontal, biologically inert, microporous plane. Such a surface, if found in the field, would indicate serious mismanagement of the land. Such mismanagement often causes rapid deterioration (often irreversible) of soil and water resources.

Field experimentalists have observed water infiltrating into natural surfaces and have been impressed with the complexity of this unique and dynamic interface. The zone immediately surrounding the air-earth interface is the most active life zone, by far, in the biosphere, being unsurpassed both in kinds and numbers of plants and animals (Dixon, 1971). These organisms profoundly influence surface microroughness, surface macroporosity, soil surface aggregation, and the water stability of soil aggregates. Although clean tillage practices may leave a surface that approaches the laboratory "ideal," modern tillage practices leave surfaces that are rough, macroporous and often covered with plant residues which feed a wide diversity of soil organisms. The smooth microporous surface produced by clean tillage in croplands often infiltrates water only 1/10 as fast as the rough macroporous surface produced by modern minimum and no-tillage practices. Overgrazing and low or no grazing in pasture lands have effects on surface conditions and water infiltration analogous to that of cropland tillage. The same can be said for forest lands with no litter and abundant tree litter at the air-earth interface. The

rough open (or litter covered) interface will infiltrate most of a 1-hour, 50-year, maximum intensity storm; whereas the smooth closed (or bare) surface sheds most of the same storm (Dixon, 1977; Hershfield, 1961). This means that land management can have a profound effect on watershed hydrology.

The air-earth interface (AEI) concept (Dixon, 1977) describes the mechanisms through which soil surface conditions control the hydraulic characteristics of the soil profile (see block diagram below).



A: Mechanisms by which surface roughness and openness control surface water transmission into a soil and subsequent storage of this water within soil pores. B: Mechanism by which effective surface head controls infiltration.

The two interrelated and interacting soil properties--surface microroughness and macroporosity--are singled out as being principally responsible for infiltration control. According to the AEI concept, these two surface conditions control infiltration by regulating the flow of air and water in underlying macropore and micropore systems. They also control the effective surface head which is defined as the ponded water depth minus the soil air pressure head (Dixon, 1975).

Satisfactory methods for directly characterizing surface microroughness and surface macroporosity for the purpose of infiltration control are not yet available. Some progress has been made in characterizing the microroughnesses associated with various tillage practices (Burwell et al., 1963). The author has tried various visual approaches to characterizing surface macroporosity. Surface macroporosity can probably be measured indirectly as the air permeability of a soil surface wherein the micropore space is water-saturated. The interacting effects of surface microroughness and macroporosity

can probably be measured as effective surface head and as mass or percent cover of plant litter. Litter would also provide a measure of the stability, equilibrium level, and generation rates of these two surface conditions.

CRITICAL RESEARCH NEEDS

Methods need to be developed or refined, or both, for characterizing surface microroughness, surface macroporosity, plant litter, and effective surface head. Since these infiltration parameters are profoundly influenced by tillage and cropping practices, they should be spatiotemporally quantified for each major land management system. Such quantification will expedite the refinement of land management systems for better protection and more efficient use of soil and water resources in crop production. Natural relationships that need to be researched include:

1. Rainwater infiltration versus effective surface head, surface microroughness and macroporosity, and plant litter.
2. Plant litter versus effective surface head and surface microroughness and macroporosity.
3. Plant litter versus populations of small soil animals, fungi, actinomycetes, and bacteria.
4. Plant litter versus macropore geometry near the soil surface.
5. Plant litter versus soil structure water stability at the soil surface.
6. Stability of microroughness versus tillage implement and surface plant residue.
7. Development of populations of soil organisms, surface macroporosity, surface microroughness versus time elapsed after mulching a bare smooth microporous surface.
8. Hydrologic behavior of microwatersheds versus tillage implement used in creating the microwatershed and elapsed time. Aspects of hydrologic behavior should include infiltration, runoff, erosion and sedimentation; and wind velocity, relative humidity, soil temperature, and soil surface evaporation. The effects of vegetative growth in seedbeds on these hydrologic parameters should be studied as a function of elapsed time.
9. Hydrologic behavior of microwatersheds formed by land imprinting rollers versus those formed by other tillage implements (Dixon and Simanton, 1977).
10. Magnitude of parameters in Kostiakov's equation (Kostiakov, 1932) versus effective surface head, plant litter, surface microroughnesses, surface macroporosity, and elapsed time after imposing surface treatment.

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INFILTRATION EFFECTS OF SOIL AIR PRESSURE

R. M. Dixon

Water infiltration into soils involves displacement of soil air with water. Such displacement is usually manifested as a simultaneous exchange of surface water and soil air across the air-earth interface. For surface water to displace soil air, the pressure of upstream soil air must rise above the ambient atmospheric pressure. Several workers have observed water movement response to air pressure changes within laboratory columns of porous media (Powers, 1934; Horton, 1940; Free and Palmer, 1940; Peck, 1965; Adrian and Franzini, 1966; and Wilson and Luthin, 1963).

These column studies and capillary tube theory lead to several obvious generalizations. In short columns, air pressure rises more rapidly but to a lower maximum than in long columns. Similarly, in coarse porous media with large pores, air pressure rises rapidly but to a lower maximum than in fine media with small pores. Under a surface having a high-bubbling pressure, air pressure rises more slowly but to a higher maximum than under a low-bubbling pressure surface. The surface may lift or rupture to reduce air pressure where a high-bubbling pressure surface caps a short column.

Theoretical analyses of infiltration often neglect the effect of displaced air pressure on the advancing wetting front (Philip, 1958; Wilson and Luthin, 1963). The simplifying assumption is usually made that the air pressure component of soil water pressure is negligible compared to the matrix or capillary component. The idea is often expressed that soil macropores readily vent displaced soil air and thereby keep the pressure to negligible levels. The authors reporting these column studies suggest that two primary field conditions are conducive to rapid soil air pressure rise. These are a large water-saturated surface area and a small antecedent soil air volume. Thus, border and basin irrigation, large ground water recharge basins, and high intensity rainfall would favor development of displaced soil air pressure; whereas furrow, trickle, and low intensity sprinkler irrigation and low intensity rainfall would produce little or no soil air pressure. The rate of air pressure rise would be increased by a small initial displaceable air volume caused by high initial soil moisture or a shallow air barrier, or both, such as a water table, wet plow sole or pan, wet clayey subsoil, cemented soil layer, impervious rock stratum or any combination of these. Field infiltrometers and rainfall simulators do not wet a sufficiently large surface to cause measurable rise in soil air pressure, since the air displaced by infiltrating water can escape freely to surrounding dry soil. One somewhat rare exception would be where the infiltrometer frame extends downward into a soil air barrier.

The Committee on Soil Physics Terminology of the International Society of Soil Science concluded that soil air pressure was not important enough under field conditions to justify inclusion in their final report (ISSS Committee, 1963; Rose, 1966). Contrary to this conclusion, the air-earth interface AEI concept (Dixon, 1972) indicates that soil air pressure interacts with soil surface conditions to give an order-of-magnitude control over infiltration. This concept states that the AEI conditions, surface microroughness and surface macroporosity, interact hydraulically to control free surface water infiltration by regulating the flow of air and water in underlying macropore and micropore systems. During the past 5 years, the infiltration role of soil air, as envisioned by the air-earth interface concept, has been verified and reported in a series of papers (Dixon and Linden, 1972a, 1972b; Linden and Dixon, 1973, 1975, 1976; Dixon, 1975, 1977; and Linden et al., 1977).

The main contributions of these papers include the (1) conception and definition of a new infiltration parameter--the effective surface head--defined as ponded water head minus soil air pressure head; (2) further verification and refinement of the AEI concept; and (3) development of closed top and "closed bottom" infiltrometers, which can produce a realistic range of effective surface heads surrounding zero head taken as ambient atmospheric pressure head. The experimental results reported in these papers show clearly that soil air is a major component of natural infiltration systems, and that the soil air pressure effect on infiltration occurs principally within the macropore system. Thus, an infiltration model, to be useful, must consider both soil air and soil macropores. To assume that soil macropores take care of the soil air pressure problem, as theorists have done, is not in the interest of advancing our understanding, prediction, and control of natural infiltration processes. However, experimentally controlling or eliminating the air pressure effect (for example, side and bottom venting of soil columns) is often useful in isolating other components of infiltration system for independent study.

CRITICAL RESEARCH NEEDS

1. Further development of closed-top and "closed-bottom" infiltrometers of both the ponded-water and sprinkled-water types.
2. Determine the range of effective surface heads occurring naturally in all major soils.
3. Determine infiltration response of all major soils to the natural range in effective surface heads using both ponded-water and sprinkled-water infiltrometers having the best open-top or "closed-bottom" design, as determined by #1.
4. Relate the effective surface heads measured in #2 to the parameters in Kostiakov's equation.
5. Determine the effective surface heads associated with major land management systems.
6. Improve old and develop new cultural practices having appropriate effective surface head levels to achieve desirable land management objectives such as infiltration, runoff, erosion, and evaporation control for improved crop stands and greater and stabler crop yields.
7. Determine effective surface heads and soil surface geometries associated with optimal routing of irrigation and rainwater into the soil for maximum crop production.

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PHYSICAL CHANGES IN SURFACE SOIL BY TILLAGE, CROP CULTURE, AND RAINFALL IN RELATION TO INFILTRATION DESCRIPTION

D. R. Linden

Tillage, plant culture, and rainfall as well as inherent soil properties influence infiltration characteristics. Most agriculturally important soils (with some extreme exceptions) would have a narrow range of infiltration characteristics if all were subjected to similar management schemes. However, management variations can affect infiltration by several orders of magnitude on a single soil. Because plant culture and tillage are controlled by man, these are tools for the management of infiltration. These manageable infiltration characteristics are also dynamic in nature and change continually with time or exposure to environmental conditions. Even though man can drastically affect infiltration by his management decisions, infiltration research on this aspect has largely been descriptive in nature.

Research is needed that describes the physical properties of natural soil systems including their particular cultural states and the changes in their physical properties with cultural practices, time, and exposure to various climatic conditions. Few definitive data are available that describe infiltration in terms of tilled soil physical properties. Definitive data on how crops, tillage, and rainfall change soil properties are also meager.

The term "infiltration description" has often been taken only to mean the description of infiltration rate as a function of time. Infiltrated water is considered as a black box called "soil water storage." "Infiltration description" should be expanded to include the distribution and disposition of infiltrated water. This is especially needed in the study of cropping systems because equal infiltration volumes under different infiltration conditions can lead to variations in amounts of water available for crop production. The distribution and disposition of infiltrated water also have consequences in leaching, ground water pollution, and soil aeration as examples of infiltration-related phenomena. Infiltration (movement across plane of soil surface), as an isolated process, is of little interest as it is only the effects of the process that are important.

Infiltration is affected by cultural state because within the soil the pore space available for waterflow and the size, shape, and continuity of pore spaces are affected. Cultural state also affects the change in this pore space by protecting or exposing the soil to environmental conditions and by encouraging or discouraging biological activity. Primary tillage operations generally create additional pore space (Allmaras et al., 1966); create rough surfaces that resist sealing, provide temporary depressional storage (Allmaras et al., 1966; Falayi and Bouma, 1975), and increased resistance to overland flow; and partly remove the protection provided by plant residue materials.

Primary tillage can thus enhance infiltration capacity (Burwell and Larson, 1969; Burwell et al., 1968; Falayi and Bouma, 1975) or can reduce infiltration if a network of highly conductive pore spaces are destroyed in the process (Ehlers, 1975). The effects of tillage are generally temporary as the soils

tend to return to a pre-tillage infiltration condition with exposure to precipitation (Burwell and Larson, 1969; Burwell et al., 1968; Falayi and Bouma, 1975). The infiltration characteristics, which are the result of a cultural state, are generally protected from sealing (change) by the presence of living or dead plant material (Duley and Kelly, 1939) whereas exposed soil surfaces seal rapidly during rainfall events (Edwards and Larson, 1969).

These infiltration responses to cultural conditions have been shown to have an effect on solute movement (Quisenberry and Phillips, 1976), available water storage (Allmaras, 1967), and runoff. Because "cultural condition" is one of the most dynamic influences on infiltration and infiltration-related phenomena, priorities should be set on obtaining definitive data on the rate and route of water movement into and within the soil in terms of soil physical properties and how these properties are affected by management and time.

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LANDSCAPE FORM AND ORDER AND SUBSOIL CHARACTERISTICS IN WATERSHED INFILTRATION DESCRIPTION - SELECTED ASPECTS

R. R. Bruce

We are interested in considering the physical character of an infiltration system and the operational processes that act upon the input variables to produce output variables (conceptual rather than empirical, Clarke, p. 4); i.e., not a "black-box" approach. Further, we are interested in the spatial distribution in the input variables as well as the spatial variation in parameters and variables characterizing the physical processes acting upon the input. There is a need to consider the nature of spatial variability and its description, whether probability-distributed variables and parameters or geometrically-distributed. A geometrically-distributed watershed model treats the watershed not as "a random assembly of different parts, but a system whose parts are related to each other by their common geomorphological history" to quote Nash and Sutcliffe (1969). Probability-distributed models describe spatial variability without reference to geometrical configuration of the points in the network at which an input variable such as rainfall is measured.

"Stochastic and deterministic methods are seen as complementary, rather than as alternatives" is a viewpoint expressed by Clarke (1973). This suggests that the method employed to describe input variables in time and space should depend upon the nature of the system, the questions to be asked and reasons for inquiry. Where a variety of scientific disciplines must be included, as in treating hydrologic systems, and none can readily apply their science factionalism, a perennial hazard exists. Clarke (1973) has provided a useful basis for renewed communication. He has recognized the terminology problem and presented some definitions that are useful. I note that Freeze (1975) has adopted these definitions. Further, he has tried to classify hydrologic models and thereby expose major differences and common features as well as assumptions. I suggest that a reading of this paper is worthwhile if you have missed it and a re-reading if you have forgotten its content.

In regard to providing a philosophical base, several writings are helpful. Philip's view of hydrology (19/5a, 1975b) I find entertaining and arresting. If one accepts hydrology as trans-science, it removes some discipline related barriers that hamper progress and suggests the need to be aware of all sciences that may bear on the questions being asked.

LANDSCAPE FORM AND ORDER

Much has been done by geologists, geomorphologists and soil scientists that bears on the question, what is the landscape form and general order of the land surface including topography and drainage. However, little has been done in answering questions about the effect of landscape form and order on hydrologic response of a selected area. Or, how the pattern of soils that have been formed in a particular landscape is related to hydrologic response has only been treated to a limited degree. I find it strange that the G. W. Musgrave article in the 1955 USDA Yearbook has formed the basis for hydrologic soil groups currently used by SCS.

The classification of soils has been a primary basis for the hydrologic response classification. Holtan et al. (1967) have written on the subject and attempted to specify what a hydrologic grouping should include. In 1970 England stated that "the most serviceable hydrologic grouping of agricultural soils is one that includes (1) the hydrologic capacity of different soils, (2) their relative position on the landscape with respect to overland and subsurface flows, and (3) their adaptability to various land uses and treatment." This was the conclusion he came to after studies reported in a 1969 paper (England and Holtan, 1969); he also found that the usual land form sequence in a watershed is flat or convex uplands, rectilinear hillside slopes and flat or concave lowlands. Three such soil-land form groups or perhaps as many as five were used to represent the hydrologic performance of watersheds. Apparently, England and Holtan extrapolated from this point to land-capability groupings. I think that this step, which may have been a matter of expediency, was an over-generalization. To look again from the viewpoint expressed early in the 1969 England and Holtan paper seems valuable.

A paper by Turner (1963) is a useful background paper where he examines the applicability of soil surveys to hydrologic response description. He comes to a conclusion worthy of note -- "None of these classifications depends on hydrologic relationships as such, although most include profile texture and structure as criteria. Most of the soil classifications are "edaphic" in purpose, the response of growing plants being the ultimate reason for the survey. Hence other factors may enter such classifications than the physical concepts required for infiltration."

Fleming and Smiles (1975) presented a view of infiltration process understanding in relation to catchment modeling. Their concluding paragraph reads as follows:

"It is believed that detailed prediction of infiltration in catchment hydrology will depend on the prediction of the space and time locations of the occurrence of ponding and hence the location and magnitude of overland flow and interflow source areas. The algorithms which incorporate these predictions will be based on conventional soil-physical principles and use information from detailed field observations. The simple two- and three-dimensional analyses using basic soil physics, such as carried out by Freeze, provide a guide to the detail required of field measurement."

The idea of identifying or circumscribing in space and time the areas of the catchment according to ponding occurrence is consistent to one degree or another with some other investigators; e.g., Smith (1976).

Several papers on spatial variability of soil properties are listed following the cited references.

SUBSOIL CHARACTERISTICS

Infiltration has been portrayed by many people through the years as a process that is entirely a function of the physical state of the surface centimeter of soil or less. This view was recently emphasized by Morin and

Benjamini (1977). However, these authors presumably restrict their discussion to bare soils. Certainly there are many situations where the hydraulic characteristics and state of the soil below the surface are relatively unimportant to infiltration. Within a landscape, however, there are many places where this is not true. Therefore, an inclusive description of infiltration must involve the subsoil. This is particularly important if questions are being asked about the amount of water infiltrated and not just questions about that not infiltrated.

Attached are a few references that deal with systems where subsoils markedly affect infiltration and hydrology. Our current thinking regarding subsoil characteristics in relation to infiltration is greatly influenced by the soil physicists who expended effort in exploring infiltration into homogeneous laboratory systems and another group relating to hydrology who focused on infiltration as it affected runoff and who became overwhelmed by the top centimeter of soil. I must conclude that a clearer definition of the system being examined and a clearer statement of the questions being asked must occur before an attempt is made to describe infiltration. Yet there is research to be done in subsoil hydraulic characteristic description as landscape infiltration is evaluated.

WATERSHED INFILTRATION

The watershed scale problem is one of specifying the heterogeneous system to a satisfactory degree for the accomplishment of a particular objective. Not only is the soil material variable with depth and area but the rainfall input is variable in time and area. Therefore, specification of the rainfall input on any designated area as well as the partitioning system composes the problem. The following is one word diagram of system aspects.

Input	System	Output
$Rainfall_{(x,y)} = f(t)$	Soil and Geologic material Space Variable Only	(i) Surface runoff - continuous or storm duration
$Rainfall_{(t)} = f(x,y)$	(a) flow characteristic	(ii) Soil water storage and distribution
Modified by canopy	(b) retention characteristic	(iii) Subsurface flow
	(c) slope	- surface channel or reservoir
	(d) relative landscape position	- water table or subsurface reservoir
	(e) dissection	

Space and Time Variable

(a) water content

(b) hydraulic gradient

(c) Matric - Natural
- Cultural

(d) surface boundary

(iv) Monthly or annual estimates

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REPRESENTATION OF INFILTRATION VARIABLES OR PARAMETERS FOR WATERSHED MODELS WITH RESPECT TO DETERMINISTIC SPATIAL VARIABILITY AND SCALE

D. L. Chery, Jr.

INTRODUCTION

The infiltration process has been conceptualized and modeled quite well at one point in space and time. For purposes of discussion, a point may be considered as a 6-in (15.24-cm) or 12-in (30.48-cm) diameter area. However, when plots 1 m square or 6 by 12 ft (1.33 m by 3.66 m), are used in infiltration tests, the significant storage in the flowing surface water distorts the measurements in respect to point infiltration rates as is recognized by some such as Rawls et al. (1976, p. 9) and Smith and Chery (1973). This storage in the flowing surface water can be accounted for in interpreting data in terms of point infiltration rate as was done by Smith and Chery (1973) and discussed by Smith (1976). This point is illustrated in figure 1.

As the area over which infiltration occurs expands to a field of a few square meters and on to drainages of many square kilometers, there is known heterogenity of soil properties, and spatial averaging or lumping of infiltration parameters becomes implicit in any model. There have been two approaches to characterization, approximation, or modeling of vertical infiltration--empirical and theoretical. A good review of some of the models representative

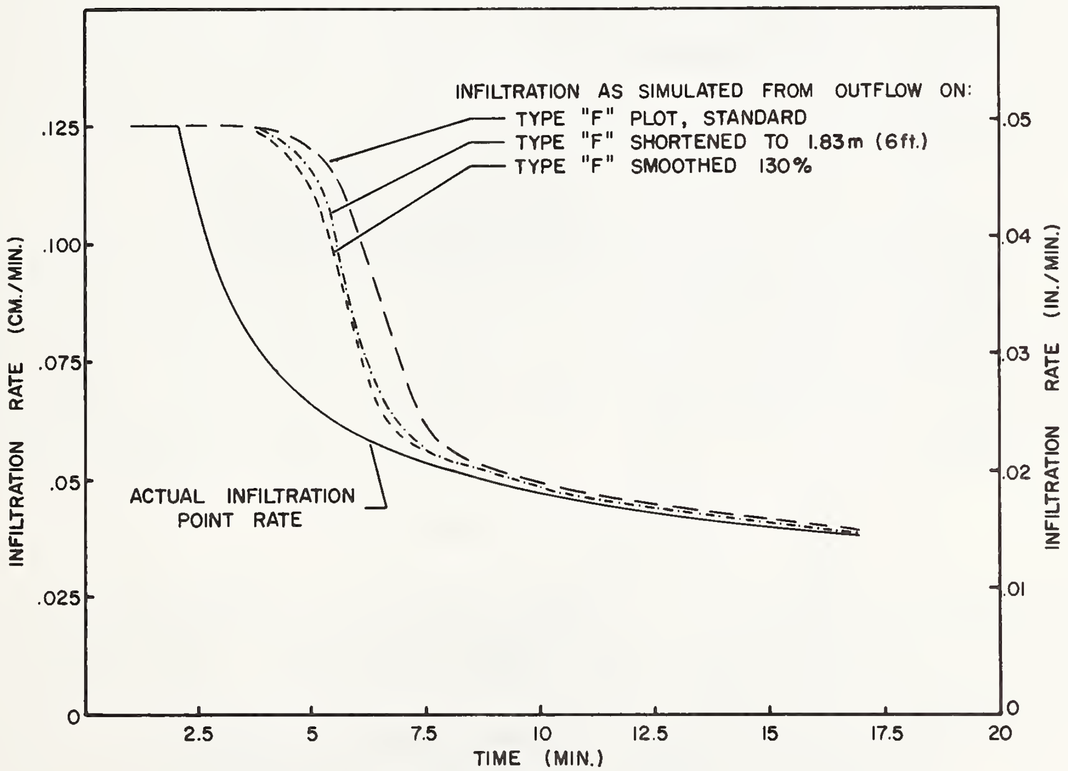

Figure 1.--Demonstration of typical time delay in comparing actual rainfall excess pattern with that measured at the lower end of an infiltrometer plot (Smith 1976).

of the theoretical and empirical approaches was made by Smith (1976). Also two categories of watershed models may be described as (1) physically based (those that are based on mathematical solution of the physics of the system to some simplified solution in which the variables are still directly related to measurable physical entities) and (2) input-output (I-O) system models (for which the transform of the input to the output is obtained from an assumed model and measurements of the input and the output signals). There will exist a range of hybrids between these two limits. In general, different considerations must be taken into account when evaluating average infiltration parameters for the two approaches.

For a given location, the soil properties can vary with time. A good illustration of this situation was detected by Chery (1976) in a watershed model evaluation that used data from SEA (ARS) location 47.002. At this site in New Mexico, infiltration was much greater in the beginning of the summer rainstorm season (May and June) than it was later in the season (July and August). The response of the June 10, 1966, storm (illustrated in figure 2)

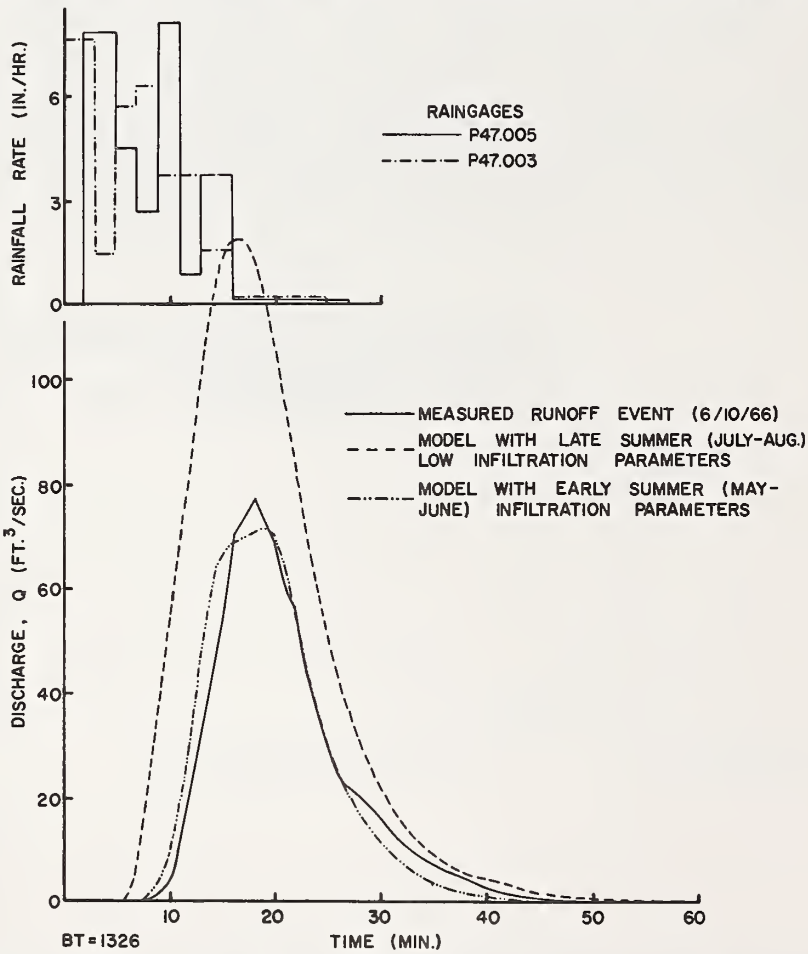

Figure 2.--Comparison of kinematic watershed model predicted discharge (for two sets of infiltration parameters) with the measured discharge of the June 10, 1966, event. SEA Location 47.002 (40-acre watershed west of Albuquerque, N.M.).

would have been more like the dashed line had it occurred in late July or August and would have been the largest flow event of record. As it was, a smaller rainstorm in August 1957 produced the greatest peak discharge. For a given area there are dynamic changes in infiltration properties and parameters. However, the concern of this workshop is the proper or adequate representation of the spatial variation in soil properties as the modeled area expands.

PHYSICALLY BASED FLOW MODELS

For physically based surface flow models such as those reported by Kibler and Woolhiser (1970) and Rovey et al. (1977) and the subsurface flow models such as reported by Freeze (1970) and Amerman (1976), the solutions are made at nodes in a finite difference grid. These solution grids have some length, ΔX, at which the solution is advanced through the space dimension of the system to eventually produce a boundary output response. This ΔX dimension is many times smaller than the overall dimension of the total area for which a solution or output prediction is sought, and at each of the nodes that are at the surface boundary, an empirical or theoretical infiltration model can be connected. Now that theoretical infiltration models have been successfully interconnected with the flow model (Smith and Woolhiser, 1971), I will pursue only that combination in developing further points in this section. The consequence of the theoretical infiltration model interconnection with the theoretical flow model being solved at nodes in a grid is that the infiltration parameters can be closely associated with porous media physical properties and the variability of these parameters need only be developed for the dimension ΔX--a significantly reduced scope of concern compared with empirical infiltration parameters as will be developed in the next section. Some evaluations of the influence on model responses due to distributions of the infiltration equation exponent $(1-\alpha)$ and final infiltration rate (f_c) have been reported by Smith (1976) and of hydraulic conductivity (K), compressibility α, and porosity n have been reported by Freeze (1975). The statistical distribution of the parameters with respect to the dimension ΔX needs to be determined. There is evidence or assumptions that many of the parameters have log-normal distributions as has been reported by Nielsen et al. (1973), Freeze (1975), and Warrick et al. (1977). However, a sobering conclusion by Freeze is that there may be no validity in making the assumption that average single values can be selected for the infiltration parameters and "hence define an equivalent uniform porous medium." (Freeze, 1975, p. 725).

INPUT-OUTPUT FLOW PREDICTION MODELS

Although the empirical infiltration relations may be interconnected with theoretical-finite grid solutions of surface and ground water flow, they are very commonly used in conjunction with an input-output (I-O) or system type of watershed model. Such models may span area dimensions of a few square meters to many square kilometers but in all practicality the lower size would be about 20 hectares (20 by $10^4 m^2$) for any major modeling or prediction endeavor. The distribution of cell areas (figure 3) into which a 242.7 mi^2 (62,869.7 hectares) watershed was divided by a consultant for distributed (non-point) source pollution study illustrates this point. The length dimension of such a unit, cell, sub-basin or however it is described is many times

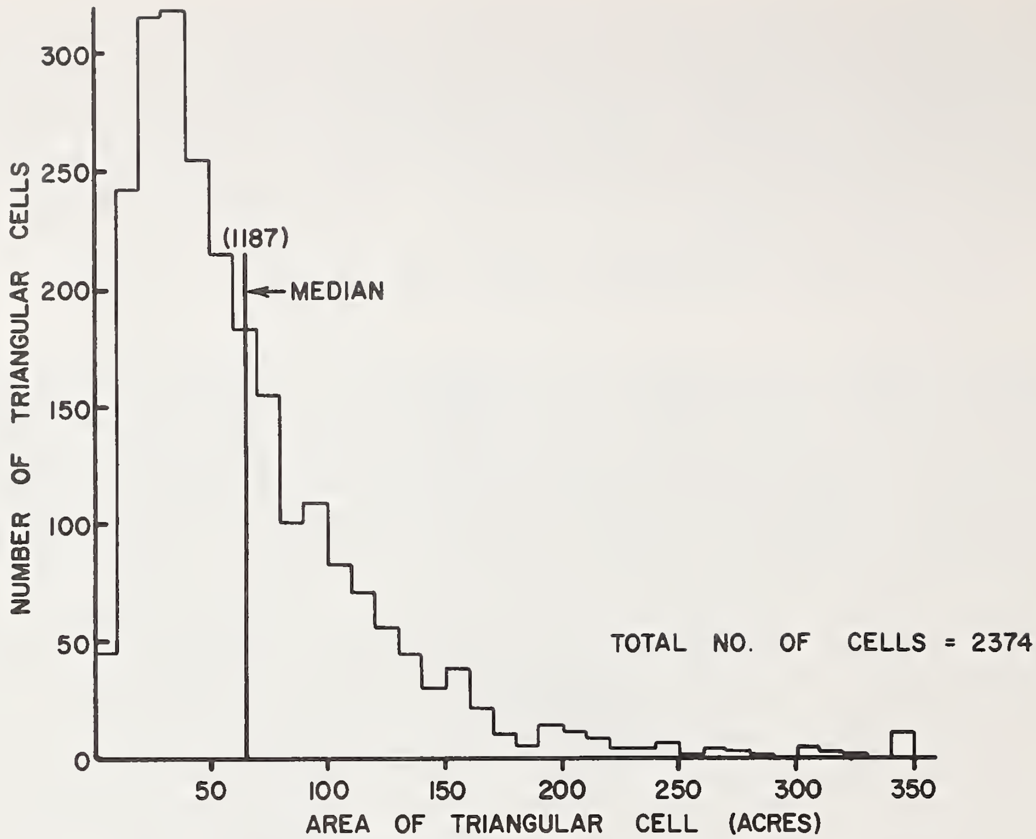

Figure 3.--Frequency distribution of triangular cell areas from the mapping Henrico 6, Va., watershed (Area = 242.7 mi^2 /62,869.7 hectares/) from the Richmond Crater Study by the ADAPT System of W. E. Gates and Associates, Inc., Grayman (1977).

that for the ΔX in the numerical solutions of the physically-based models. As an example, the watershed modeled by Chery (1976) had an area of 40 acres (16.19 hectares). The length dimension of main channel extended to end of the watershed is 2870 ft (874.8 m) whereas the longest ΔX in solution of overland flow was 58.7 ft (17.9 m), which is 2 percent (2.04 percent) of one total watershed length dimension. The parameters of these empirical relations when used with input-output models are a function of the total watershed area and magnitude (volume and/or rate) of the input. This latter point was illustrated by Chery (1976) in a derivation of a simple input-output model from a complex physically-based watershed surface flow model. Where the physically-based model had a slight consistent over-prediction of volume (figure 4) the simple model progressively over-predicted the flow volume as the input volume decreased (figure 5). This over-prediction with decreasing size of rainfall event resulted, principally, from the inability of the simple I-O model to represent infiltration from flowing water over the surface and in the channels after a point rainfall excess had been generated by the infiltration relation. The determination of infiltration parameters for empirical formulations will intrinsically attempt to compensate for this situation and will be based depending on the spectrum of input rates used to obtain the fitted infiltration parameters.

Probably this effect becomes more pronounced as the area increases and thus the parameters of infiltration equations used in such models also are dependent on the absolute size of the area. For discussion purposes, the infiltration equations of Horton (1940), Soil Conservation Service (SCS 1964), Holtan et al. (1974) and Snyder (1971) are among those that I will classify as empirical. The parameters of many of these infiltration relations are not associated with single measurable physical properties but encompass a combination of soil properties, cover, and cultural practices, i.e., the CN parameter in the SCS procedure (SCS 1964) or the 'a' parameter in the retention function (Snyder, 1971; Mills et al., 1976). Consequently if these parameters are to be evaluated with respect to the distribution of values over a watershed area of the several variables encompassed by the single lumping parameter, the complexity of the joint distributions will have to be unraveled, another dimension of complication.

In addition to the profound influence of 'area' on the infiltration parameters, the lumped parameter character of many empirical infiltration relations must also be considered.

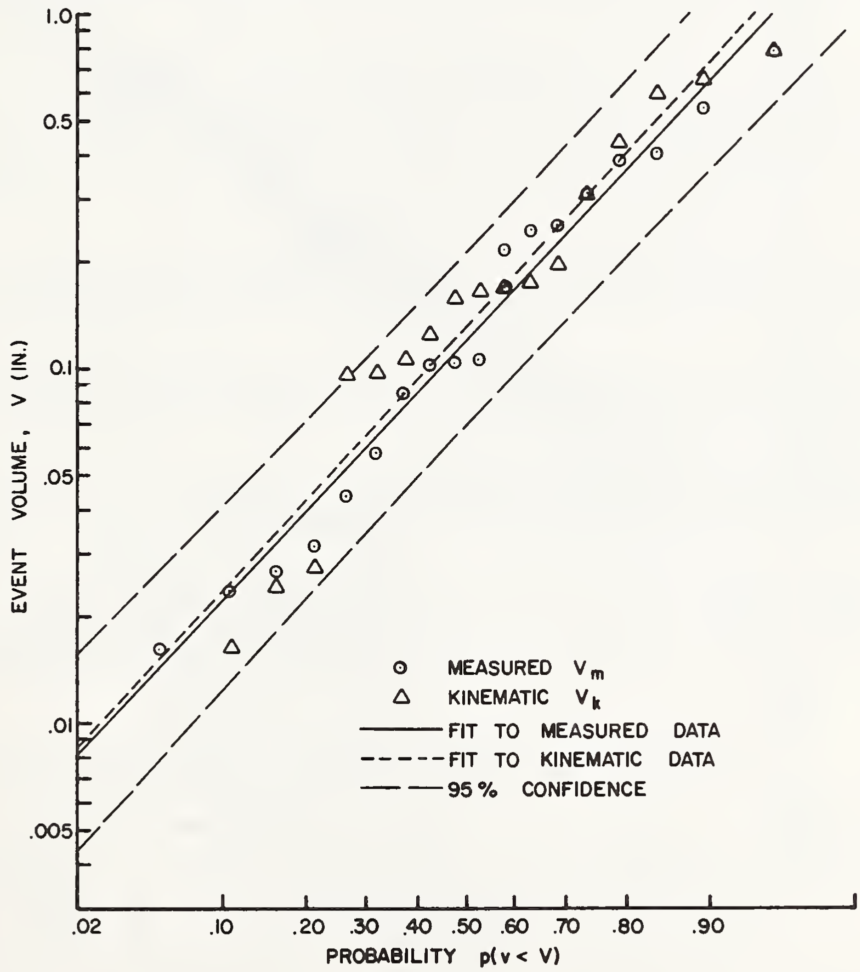

Figure 4.--Log-normal probability distribution of predicted event volumes for the kinematic model compared with that of 18 selected measured events.

ANOTHER PROBLEM

For all the concern about understanding and representing the distribution of infiltration parameters in space, the researcher must maintain in perspective the fact that the variability in space of the input and initial conditions may be of a much greater magnitude and of greater significance than the spatial variability of the infiltration parameters. This difficulty was experienced by Chery (1976) in a model evaluation where two raingage samplings of a rainstorm, that caused the largest peak discharge from a 40-acre (16.19-hectare) watershed, did not adequately describe the rainfall input. The situation has also been discussed by Smith (1977).

SUMMARY - CONCLUSION

The development of research programs, to better define or assign representative values to parameters of infiltration equations, must discern between the type of infiltration equation, empirical or theoretical, and the type of

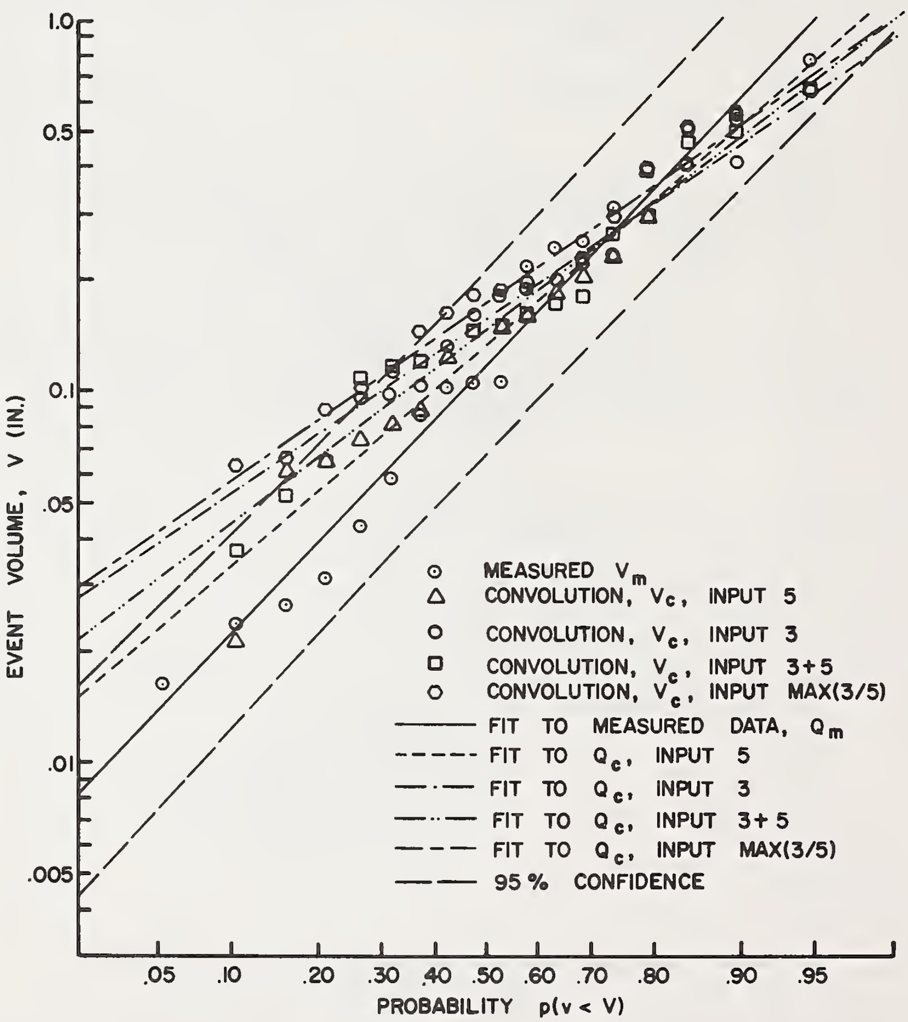

Figure 5.--Log-normal probability distribution of predicted volumes for the convolution model (with four different input sets) compared with that of 18 selected measured events.

watershed model with which it will be used. The parameters of theoretical infiltration models are more directly associated with measurable soil properties. Further, when they are used with nodes of a finite grid solution for a flow model, the space dimension is relatively small, and it may be considered relatively constant in respect to the total area variations of the set of watershed sizes. With these types of models, the concern about the statistical distribution of soil properties has relevance. However, empirical infiltration formulae used in conjunction with input-output models have the confounding property that the parameters also become functions of input rate and absolute size of the modeled watershed. In the course of designing infiltration research it may be necessary in this latter situation to separate the infiltration model from the many-faceted compensating role that it assumes and separately "study the possibility of developing compensating coefficients for the discrete 'non linear' model (or any system model) convolution that would be functions of excess rate and rainfall distribution" (Chery 1976, p. 138). In view of previous discussion, it is suggested that the dependency of the parameters on the area of the watershed also be investigated.

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TEMPORAL AND SPATIAL DESCRIPTION OF SOIL WATER ON WATERSHEDS WITH VARIABLE VEGETATION AND CULTURE

W. J. Rawls

The inaccuracies that arise in the computations of watershed models (both physically and parametrically based) can frequently be traced to inadequate temporal and spatial representation of hydraulic properties of the soil and the initial soil water content.

One approach to this problem which has been used on a limited and fragmented basis has been the use of historical point data or average data to describe the spatial and seasonal distribution of soil water for various soil-vegetation complexes. Schreiber and Sutter (1972) used daily rainfall to describe the time distribution of available soil water in a warm season rangeland. Rawls et al. (1973) used long-term soil water data to determine seasonal soil water trends and variations for various soil, vegetation and precipitation zones. Rogowski (1972b) illustrated how soil water data could be grouped into seasonal frequency distribution curves. McGuinness and Urban (1964) illustrated the wide variability of soil moisture in a small area and the large number of samples necessary to statistically represent the area. It has been suggested that statistical techniques such as factor analysis, cluster analysis and discriminate analysis can be used to spatially group soil water measurements.

Another method for describing the spatial description of soil water has been through the use of physically based models in which the variability of the hydraulic properties of the soil are used. Various authors such as Nielsen et al. (1973), Rogowski (1972a), Jeppson et al. (1975), and Warrick et al. (1977) have tried to measure and describe the variability of soil properties in the field. Rogowski (1971, 1972b), Peck et al. (1977) and Jeppson et al. (1975) have attempted to use the variability in models that describe the soil water characteristics. However, information on the distribution and statistics associated with hydraulic conductivity, soil water content and soil water pressure over an area for various soil conditions is not available.

Future research in the temporal spatial variability of soil water should include:

(1) Determine the distribution and statistics associated with the spatial hydraulic properties of the soil.

(2) Determine the accuracy requirements of the hydraulic properties of the soil needed to describe areal infiltration.

(3) Develop the necessary statistical sampling procedures to describe areal infiltration.

(4) Develop approximations describing the spatial hydraulic properties of the soil that meet the accuracy criteria.

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MULTI-DIMENSIONAL FLOW -- ITS QUANTIFICATION ON LARGE AND SMALL SCALE

A. W. Thomas

Interflow has been defined as that part of precipitation that infiltrates into the soil, moves through the permeable surface layer and returns to the surface above the gaging station (Minshall and Jamison, 1965). Wilson and Ligon (1973) define it as flow that takes place as the result of a perched water table. There appear to be two primary conditions necessary to cause interflow: (1) a layered profile with a less permeable layer underlying a permeable surface layer and (2) soil water content in the more permeable layer reaches saturation.

A search of the literature has been made which primarily deals with interflow or lateral flow, or both. The references relate to interflow as defined above, but hopefully they contribute to understanding the principles of the more inclusive topic, multi-dimensional flow. The following discussion is divided into the following three parts: (a) experimental and theoretical studies of waterflow in an inclined soil slab, (b) experimental studies of interflow on small field scale sites, and (c) large scale multi-dimensional waterflow modeling.

INCLINED SOIL SLAB STUDIES

Luthin and Day (1955) reported an experimental study where lateral flow was the main focus. Klute et al. (1965) followed with their well known analysis of waterflow in a saturated inclined soil slab and established a starting point for the understanding of lateral flow. Quite a few others have followed with various modifications of Klute's problem. However, they hinge together with the following three common assumptions: (a) the soil surface is inclined, (b) the bottom and two ends of the soil slab are impermeable and (c) two-dimensional flow is assumed. Significant differences in the study of the inclined soil slab problem can be summarized as follows:

(1) Steady-state, saturated flow, homogeneous soil; Klute et al., 1965.

(2) Steady-state, saturated or unsaturated flow, homogeneous soil; Whisler, 1969.

(3) Steady-state, saturated flow, multi-layered soil; Selim (1975), and Selim et al. (1975).

(4) Unsteady-state, saturated and unsaturated flow, homogeneous soil, Nwa et al. (1973), Nutter (1975), Hewlett and Hibbert (1963).

Yang (1976) has summarized many of the significant findings from the studies of the inclined soil slab. From the literature he has grouped the findings under the following headings:

Factors affecting total interflow rate
Factors affecting size of the area having inward flux
Interflow from an unsaturated soil slab
Interflow versus surface runoff
Location of the inward flux of water

A fair question is -- what value is our understanding of the flow in the inclined soil slab in solving problems related to interflow in natural landscapes? There are two major concerns that I find:

(1) Boundary conditions are quite different. This is especially true when assuming an impermeable boundary at the down-gradient end of the soil slab.

(2) Initial soil water conditions and surface flux conditions (infiltration) have received little attention. Our observations at Watkinsville indicate that initial soil water conditions and rainfall character play a vital role in the occurrence of interflow.

FIELD-SCALE INTERFLOW STUDIES

Minshall and Jamison (1965) analyzed runoff characteristics from two watersheds (27 and 50 acres) on claypan prairie soils in Illinois. They found that runoff measured at a gaging station may include water that enters the soil upslope and returns as interflow downslope. Their data attest to the existence of gains from interflow or quick-return flow on Midwest claypan soils under conditions of high antecedent soil water. No evidence of interflow was found on high-intensity summer storms of short duration with low antecedent soil water.

Dunne and Black (1970) reported an experimental study on three small watersheds in Vermont. They were interested in the magnitude and timing of subsurface contributions to channel runoff and the conditions under which significant amounts of subsurface stormflow are produced. They differentiated return flow from subsurface flow by defining return flow as the water that infiltrates but returns to the surface above the channel. They found that subsurface stormflow occurred in large storms but was not an important contributor to total storm runoff despite conditions favorable to its existence. Their data indicate that subsurface flow contributes little to the storm runoff; however, return flow may be significant. In a control test they found that subsurface stormflow contributed between 1 percent and 5 percent of the peak runoff while return flow contributed almost 50 percent of the peak rate.

Weyman (1973) studied the downslope flow of water in soil on a convex hill. He was interested in describing the water flow and in determining the conditions for its existence; he concluded:

(1) The response of the hillslope to rainfall was dominated by saturated through-flow within the mineral layers of the soil.

(2) There was no evidence to suggest that lateral unsaturated flow contributed to the storm response.

(3) Unless the wetting front was saturated, the initiation of saturated lateral flow was dependent upon some break in the vertical permeability profile.

(4) The response of the hillside to rainfall was delayed because the lateral flow system was some depth below the surface and the peak discharge was relatively low.

(5) Because downslope flow during drainage resulted in an upslope water gradient, the zone of saturation expanded during the course of a storm in the form of a wedge.

(6) During drainage the saturated zone contracted and was replaced by a vertical unsaturated flow to an unsaturated lateral flow system in the B/C horizon.

(7) Once the unsaturated flow dominated the slope, discharge continued for prolonged periods.

Wilson and Ligon (1973) studied interflow on a Piedmont watershed in South Carolina. They wanted to determine the principal controlling factors responsible for interflow and to develop some means of predicting interflow rates and amounts based on precipitation and soil characteristics. Wilson and Ligon state that interflow is apparently a significant part of winter and spring runoff in the Piedmont and also occurs in the Coastal Plain and along the Atlantic and Gulf Coast regions. They believe that interflow is a part of the runoff which occurs when baseflow is at its highest level and when surface runoff is most likely to occur. It has little influence on peak rates of runoff but is significant in total runoff. They concluded that the "A" horizon must be near or at saturation and the "B" horizon must be near field capacity for interflow to occur in significant amounts. They estimated the volume of interflow to be 10 percent of the volume of surface runoff. They found that working with a daily soil water balance model, assisted with an hourly balance model during critically wet periods, the occurrence of interflow could be predicted with reasonably good accuracy, and the volume of interflow could be predicted with less accuracy.

MULTI-DIMENSIONAL WATER FLOW MODELING

To include ground water flow problems may seem to be a departure from the previous discussion. However, this seems to be the only direction at the next scale of the landscape. Literature abounds in this general area, but to conserve space I will only mention Freeze's work. He has written extensively on the general subject, and I find his present philosophy interesting.

Freeze has analyzed the steady-state regional ground water flow problem (three-dimensional, nonhomogeneous, and anisotropic basin) by the numerical finite difference approach in great detail. He has looked at transient flow, saturated and unsaturated flow, confined and unconfined aquifers, and perched water table conditions. One of the major problems associated with such modeling activities is the required hydrologic characteristics of large segments of the geologic materials. Until recently he has maintained that single-valued parameters could characterize large segments of the earth. He now questions this hypothesis.

In his recent paper, Freeze (1975) states that his recent study "throws into question the validity of the hidden assumption that underlies all deterministic ground water modeling; namely, that it is possible to select a single value for each flow parameter in a homogeneous but nonuniform medium that is somehow representative and hence define an 'equivalent' uniform porous

medium. For transient flow there may be no way to define an equivalent medium." He believes that the most realistic representation of a naturally occurring porous medium is a stochastic set of macroscopic elements in which the values of the three basic hydrogeologic parameters (hydraulic conductivity, compressibility, and porosity) are defined by frequency distributions. Certainly this approach does not simplify the problem since there are two types of uncertainty associated with this type of deterministic modeling.

(1) What are the properties of the statistical distributions of the output variables arising from a deterministic ground water flow model when input parameters are specified as statistical distributions taken from known populations?

(2) What additional uncertainties or reductions in confidence are introduced into the solutions by the fact that input population distributions are not known but must be estimated from the available statistical samples?

CONCLUDING REMARKS

Interflow or multi-dimensional flow, or both, have been briefly discussed on three general scale levels. As is the case for many natural systems, when we leave the theoretical and controlled laboratory studies, we become uncertain about the system response and many of the processes that operate therein. In terms of understanding interflow and its role in hydrology there appears to be one major need -- further field experimentation. A sound conceptual basis is needed especially in evaluating subsurface flow as it impacts water quality problems.

Interestingly enough, infiltration has not been discussed. Infiltration and complexity in the soil surface conditions that influence infiltration have hardly been mentioned in terms of impact upon the interflow or lateral flow process. Only indirectly has infiltration been discussed in the literature cited in this discussion. This general area is of concern to us at Watkinsville, where we are actively engaged in studying some specific problems.

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INFILTRATION RESEARCH IN AUSTRALIA

M. L. Sharma

Infiltration has long been recognized as an important process and has attracted considerable attention. Although some empirical expressions have been developed and used, major research efforts have concentrated on developing analytical solutions of the Richards-type water flow equation. The mathematical models have been derived for idealized systems and attempts have been made to extend these to real field situations. The models have been tested in the laboratory and in the field and applied on an areal basis.

Following are a few simplified equations developed for one-dimensional infiltration into homogeneous soils under water ponding conditions:

(a) Philip's (1957) two-parameter equation relating infiltration rate (v) to time (t) is:

$$v = \tfrac{1}{2} St^{-\frac{1}{2}} + A \tag{1}$$

where S is sorptivity, A is a parameter that for early stages of infiltration can be approximated by $A \doteq 1/3\ k_s$. Here k_s is saturated hydraulic conductivity or steady state infiltration rate. Equation (1) fails at long times.

(b) For linearized diffusivity, Philip (1969) derived an equation:

$$V = \left[\tfrac{1}{2} (\pi T)^{\frac{1}{2}} e^{-T} - \operatorname{erfc} T^{\frac{1}{2}}\right] \tag{2}$$

where $V = (v - k_s)/k_s$, $T = k_s^2\ t/\pi\ S^2$

(c) Assuming diffusivity $D(\theta)$ is described by a delta function, as is the case in the Green and Ampt equation, Equation (2) takes the form:

$$2\pi\ T = \ln\left[V/1 + V\right] + 1/V \tag{3}$$

(d) Recently, Collis-George (1977) derived a semi-empirical expression for cumulative infiltration (I) as follows:

$$I = I_o\ (\tanh \tau)^{\frac{1}{2}} + k_s t \tag{4}$$

where $I_o = S\ (t_c)^{\frac{1}{2}}$, $\tau = t/t_c$, t_c is an empirical constant.

A procedure for evaluating t_c is outlined by the author. Equation (4) resembles the integral form of Equation (1), but is supposed to be valid for the full time range.

Note that all the above expressions have two common parameters, S and k_s (if A is assumed to be some fraction of k_s). The attraction of these equations for field infiltration rests on how closely the boundary conditions can be

realized and how rapidly and reliably these parameters (S, k_s, A) can be evaluated in situ.

These equations have been tested against experimental results in laboratory packed columns and in the field (e.g., Talsma, 1969; Talsma and Parlange, 1972; Smiles and Knight, 1976). The linear solution (2) is reported to fit the field data best; however, Swartzendruber and Youngs (1974) consider equations 1 through 3 to be acceptable. An argument is that Equation (1) is to be preferred for ease of computation and because of its capability to express t as a function of v. Therefore, Equation (1) has been most widely tested and used. Rapid and reliable methods for evaluation of the two parameters (S, k_s) have been reported for a wide range of soils (Talsma 1969).

EXTENSION OF THEORY TO NONIDEALIZED SYSTEMS

All the above equations apply to rigid soils. But in swelling soils, an additional component of water potential, overburden pressure, is experienced because water content change is accompanied by vertical displacement of soil. Philip (1969) derives an expression for swelling soils which is equivalent to (1). In terms of Equation (1), the transition from $I \alpha t^{\frac{1}{2}}$ to $I \alpha t$ is rapid when S/A is small, as is often the case in coarse and medium textured soils. By contrast, in clay soils S/A is large (Smiles, 1974) and therefore $I \alpha t^{\frac{1}{2}}$ persists for long periods (Talsma, 1976; Sharma and Tunny, 1977). Thus in swelling soils, the influence of the gravity term is small and infiltration has similarity to the process of capillary rise in rigid soils. However, difficulties are usually associated with the presence of cracks which are not accounted for in the theory.

Philip (1969) considers cases of stratified profile, but no simple analytical solutions are available. A modified Green and Ampt approach, or Equation (3), could be applied for situations where k_s decreases with depth. However, for situations where k_s increases with depth, the approach fails. Under these conditions and situations where water content varies greatly in the profile, numerical solutions need to be used.

Soil air may be entrapped ahead of the wetting front and this will tend to inhibit infiltration and would cause Equation (1) to fail. At present, no analytical solutions for describing infiltration in these situations are known. Philip (1975) and White et al. (1976) explore some aspects of instabilities and viscous fingering.

INFILTRATION IN RELATION TO HYDROLOGY

In the context of hydrology, boundary conditions of "variable flux" are experienced and the rate of water supply to the soil surface varies in time and is frequently less than is required to maintain ponded conditions. Depending on rainfall intensity (v_r), this gives rise to three possible situations, that is, nonponding ($v_r < k_s$), pre- and post-ponding ($v_r > k_s$). These can be solved numerically; however, analytical solutions are available only for some simple $D(\theta)$, $k(\theta)$ functions (Philip 1974).

The transition of preponding to ponding stage of infiltration under natural rainfall is of fundamental importance to hydrologists. Assuming that the wetting front under preponding behaves identically with ponded infiltration, except for surface water content, then ponding will start when $v_r = dI/dt$. The equivalent time to ponding, t_p, according to Fleming and Smiles (1975) can be calculated for rainfall rate, v_r from Equation (1)

$$t_p = S^2/4\,(v_r - A)^2 \tag{5}$$

The validity of a similar approximation has been investigated by Mein and Larson (1973) using the Green and Ampt equation. Reeves and Miller (1975) have termed this approach the "time compression approximation" and show that it is valid even for erratic rainfall.

Chapman (1970) modified Equation (1) for hydrologic modeling by assuming sorptivity ($S_{\theta i}$) at the initial moisture content (θ_i) to be a function of the soil water deficit, $\theta_s - \theta_o$, that is,

$$S_{\theta i} = S_o\,(\theta_s - \theta_i)/\theta_s \tag{6}$$

where S_o is a constant equivalent to S at $\theta = 0.0$. Chapman then uses Equation (1) to derive a mean infiltration capacity $\bar{v}$, over each time step in the model. If $\bar{v} > v_r$, a preponding situation is assumed, t in Equation (1) is set to zero, previously infiltrated water is distributed over the soil store and a new value of $S_{\theta i}$ is computed. If $\bar{v} < \bar{v}_r$, infiltration in the time step equals $\bar{v}$ and post-ponding occurs, so the time step is added to "t" and $S_{\theta i}$ remains unchanged for the calculation of $\bar{v}$ in the next time interval.

Dunin and Costin (1970) outline a method for calculating S and k_s values from hydrographic analyses of runoff events from a catchment.

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STATUS OF INFILTRATION RESEARCH AND MEASUREMENT

IN THE UNITED STATES, 1977

C. R. Amerman

In research planning, to know what has been accomplished in the area of particular interest is vital and to know what others are doing at the time of the planning process is quite helpful. This is an attempt to assess what others are currently doing in the way of infiltration research and measurement.

Information was gathered by querying the U.S. Department of Agriculture Current Research Information System (CRIS) using the word "infiltration" as the primary keyword. Other keywords included precipitation, snowmelt, and simulation. The current year's reports of the CRIS system were scanned for their relevance to water infiltration into soil, and complete reports were obtained of those found to be of interest. The series of reports for each relevant project were studied, and the projects were classified according to several categories thought to be helpful in the planning process.

The CRIS system inquiry was supplemented with letters to each of the State water resource centers (WRC's) and to each of the USDA-SEA field stations thought to be engaged in some phase of infiltration research or data collection. WRC and SEA replies were classified in the same scheme as the CRIS reports.

In many cases the replies from the WRC's and from SEA simply corroborated what was already in the CRIS system. Some CRIS projects are very broad in scope, however, and a number of the letter replies reported infiltration research which is probably conducted under CRIS work units that do not specifically mention infiltration. There are undoubtedly some research projects incorporating infiltration that have not been identified by the queries.

Listed in table 1 are all known projects according to a series of general subject matter contexts for which infiltration is thought to be relevant. In table 2 infiltration research is categorized by type (the major headings) and by more specific subject matter context (minor headings) than is given in table 1.

Categorization of projects was based solely on what appears in CRIS reports and replies to the queries to the WRC's and SEA locations. Because of the number of projects, the author's interpretations of these documents have not been checked with individual project holders.

Table 3 contains complete identification for each CRIS project in numerical order by accession number. Table 4 contains addresses of each WRC and SEA correspondent given in tables 1 and 2. Information about a project listed in tables 1 or 2 may be obtained using the addresses given, or if it is a CRIS project, by giving the accession number to CRIS and asking for the file of progress reports.

A total of 105 CRIS work units are listed in table 3. Some of these refer to infiltration in their objectives or approach statements, indicating an intention to consider infiltration, but do not mention infiltration in their progress reports. Thus the importance of infiltration research in the

105 work units varies from simple acknowledgment that it ought to be considered to the role of a major objective.

The first category of table 2, Infiltration Research, is particularly revealing regarding research in which the infiltration phenomenon itself is of primary interest. Twenty-nine projects are listed in this category (some more than once under different subheadings). Seventeen of these deal with simulation and three with instrumentation, thus are not, presumably, intended to reveal significant new knowledge regarding infiltration as a mechanism. Of the 105 CRIS projects, only six might be said to be attempting to develop new knowledge about infiltration. Three more "new knowledge" studies not positively identified through the CRIS system were found in the replies from the WRC's and SEA locations.

The second category of table 2, Infiltration Measurements, contains references only to reports that specifically mention measurements. The most frequent method of measurement was by some type of sprinkling infiltrometer. About half as many projects rely on flood infiltrometers. A number of projects use both techniques. Projects relying on such indirect measurement techniques as the volume-balance method and calculations based on measured soil parameters were nearly as numerous as those using flood infiltrometers.

Only 18 system modeling projects refer to infiltration as a component. This is an indication that the CRIS, WRC, and SEA queries may have missed full coverage of an important segment of infiltration research. Models involving surface and ground waters are currently developed in such diverse university divisions as civil engineering, geography, geology and variously named ecological departments. The water resource centers in each state should be aware of such efforts, but very few referred to them.

Of the 18 system modeling projects, more than half are directed mainly at hydrologic systems. Four involve the movement of chemicals and two are concerned with simulating plant growth.

In 16 projects, infiltration is an independent variable thought to influence such things as crop production, nutrient movement and irrigation efficiency.

Seventy-two projects include infiltration as a dependent variable. Nineteen of these projects recognized infiltration in objectives and approach statements, or both, but apparently did not come up with results of enough significance to be noted in progress reports. Also, these 72 projects were primarily concerned with such topics as tillage or waste disposal rather than infiltration. Nevertheless, it is interesting to note that, although only nine projects were identified with infiltration process research, between one-half and one-third of all projects reported attempts or intentions to determine how infiltration is influenced by various land treatments and conditions.

In nearly all the projects considering infiltration as a dependent variable, essentially empirical methods were used. This observation is supported by the relatively large number of projects listed in both categories 2 (measurement) and 5 (dependent variable).

Categorization of table 2 was not detailed enough to reflect the fact that there is a large variety of types of infiltrometers available and under development. This, coupled with the apparent necessity to measure infiltration under each new surface condition or treatment, may be an indication that the infiltration process or mechanism itself is poorly understood.

In developing a research plan for broadening knowledge of the infiltration process, the most pertinent current projects appear to be those listed in table 2 under Infiltration Research.

Again, this discussion has depended almost exclusively upon the author's interpretations of very brief sketches contained in CRIS reports and letters. Thus, some projects may be misclassified and some of the tallies given herein may be inexact. However, the relative proportions of the number of projects devoted to or including various aspects of infiltration research should be closely approximated.

Table 1. Infiltration Research by Primary Context[1]

CLAY MINERALOGY

59165; Oregon State University; Corvallis

CROP PRODUCTION

40385; Auburn University; Auburn, Ala.
57173; Auburn University; Auburn, Ala.
65664; University of California, Davis
60689; Kansas State University, Manhattan
55218; Montana State University, Bozeman
30927; Pennsylvania State University, University Park
32447; South Dakota State University, Brookings
10465; Colorado State University, Fort Collins
60735; Oregon State University, Corvallis

EROSION

66510; University of California, Davis
71005; Purdue University; West Lafayette, Ind.
40833; SEA; Ames, Iowa
55453; Iowa State University, Ames
42240; SEA, Morris, Minn.
40768; SEA; State College, Miss.
18928; SEA; Pendleton, Oreg.
70678; Texas A&M University, College Station
65076; Virginia Polytechnic Institute and State University, Blacksburg
42016; SEA; Prosser, Wash.
Nevada, Reno; Peterson

[1]Numbers are CRIS accession numbers. See table 3 for list and complete identification of CRIS projects referenced. Lines without numbers refer to research descriptions received by mail. The last item on such a line is the name of the correspondent. See table 4 for list of complete addresses of correspondents.

Table 1 (continued)

EVAPOTRANSPIRATION

Oklahoma, Stillwater; Stone

FORESTRY

5835; University of Arizona, Tucson
32070; University of Hawaii; Honolulu
68217; University of Hawaii; Honolulu
61397; Ohio Agricultural Research and Development Center; Wooster
64993; Utah State University, Logan
152; U.S. Forest Service; La Crosse, Wis.

GROUND WATER

18629; SEA; Boise, Idaho

HYDRO-CHEMICAL MODELING

70437; University of Florida, Gainesville
40921; SEA; Watkinsville, Ga.

HYDROLOGIC SIMULATION

20758; SEA; Fort Collins, Colo.

HYDROPHOBIC SOILS

3824; University of California, Riverside

INFILTRATION DATA

Illinois, Urbana; Stout
South Carolina, Clemson; Ligon
Washington, Pullman; Gardner

IRRIGATION

58968; University of Arizona, Tucson
64509; University of Arizona, Tucson
23439; University of Arkansas, Fayetteville
8900; University of California, Berkeley
43109; University of California, Davis
65149; University of California, Davis
66758; University of California, Davis
67103; University of California, Davis
1189; University of Hawaii, Honolulu
64706; University of Hawaii, Honolulu
30831; Agricultural Experiment Station, Farmington, N.M.
66136; New Mexico State University, Las Cruces
60735; Oregon State University, Corvallis
64832; Oregon State University, Corvallis
32447; South Dakota State University, Brookings
63555; Utah State University, Logan
20799; SEA; Prosser, Wash.
42016; SEA; Prosser, Wash.
Maryland, College Park; Green
Utah, Logan; Willardson

Table 1 (continued)

LAND TREATMENT

19425; SEA; Fort Collins, Colo.

PLANT GROWTH MODEL

41853; SEA; Temple, Tex.
67327; Clemson University; Clemson, S.C.

PUBLIC RECREATION

66086; Ohio Agricultural Research and Development Center, Wooster

RANGELAND

20755; SEA; Tucson, Ariz.
20756; SEA; Tucson, Ariz.
139; U.S. Forest Service; Riverside, Calif.
20867; SEA; Twin Falls, Idaho
19422; SEA; Sidney, Mont.
67518; Oregon State University, Corvallis
70678; Texas A&M University, College Station
18629; SEA; Boise, Idaho

SEEDLING EMERGENCE

66138; Texas A&M University, College Station

SOIL AND WATER CHEMISTRY

18926; SEA; Brawley, Calif.
67103; University of California, Davis
66136; New Mexico State University, Las Cruces
61131; Pennsylvania State University, University Park
65246; Utah State University, Logan
62941; University of Wisconsin, Madison
60187; Purdue University; West Lafayette, Ind.

SOIL DRAINAGE

42735; Ministry of Agriculture; Giza, Egypt

SOIL FREEZING

67506; North Dakota State University, Fargo
61645; Cornell University; Ithaca, N.Y.
Idaho, Moscow; Molnau

SOIL PHYSICAL PROPERTIES

69523; Iowa State University, Ames
68197; Kansas State University, Manhattan
67918; North Carolina State University; Raleigh
4394; Oregon State University; Corvallis
60573; Virginia Polytechnic Institute and State University, Blacksburg

Table 1 (continued)

SOIL RESOURCES

Kansas, Manhattan; Powers
Maine, Orono; Rourke
Minnesota, St. Paul; Swan
Mississippi, Mississippi State; Whisler
Nevada, Reno; Peterson
North Dakota, Fargo; Sweeney
Ohio, Columbus; Petro
Tennessee, Knoxville; Sewell

SOIL WATER MOVEMENT

2608: University of California, Davis
3824; University of California, Riverside
18640; SEA; Fort Collins, Colo.
61852; Connecticut Agricultural Experiment Station, New Haven
1189; University of Hawaii, Honolulu
1373; Purdue University; West Lafayette, Ind.
42016; SEA; Prosser, Wash.
21346; Technion Research and Development Foundation; Haifa, Israel
Washington, Pullman; Gardner

STRIP MINING

70190; Iowa State University, Ames
69576; University of Kentucky, Lexington
71279; New Mexico State University, Las Cruces
61397; Ohio Agricultural Research and Development Center, Wooster
69578; Ohio Agricultural Research and Development Center, Columbus
143; U.S. Forest Service; Logan, Utah
71317; West Virginia University, Morgantown
Pennsylvania, University Park; Cunningham

TILLAGE

71005; Purdue University; West Lafayette, Ind.
40833; SEA; Ames, Iowa
55453; Iowa State University, Ames
68197; Kansas State University, Manhattan
22767; University of Minnesota, St. Paul
40910; SEA; Morris, Minn.
68030; Oklahoma State University, Stillwater
18928; SEA; Pendleton, Oreg.
42906; SEA; Pendleton, Oreg.
30927; Pennsylvania State University, University Park
27364; University of Wisconsin, Madison
64448; University of Wisconsin, Madison
41406; Institute for Agricultural Research; Novi Sad, Yugoslavia
Idaho, Moscow; Molnau

TURF

63382; University of Massachusetts; Amherst
69608; Washington State University; Pullman

Table 1 (continued)

WASTE DISPOSAL

40694; SEA; Phoenix, Ariz.
23439; University of Arkansas, Fayetteville
18926; SEA; Brawley, Calif.
55509; Cornell University; Ithaca, N.Y.
69578; Ohio Agricultural Research and Development Center; Columbus
64644; University of Vermont, Burlington
61302; University of Wisconsin, Madison
32018; University of Wisconsin, Madison
Michigan, East Lansing; Burton
Pennsylvania, University Park; Cunningham

WATER YIELD UNDER ARID CONDITIONS

19663; Hebrew University of Jerusalem; Rehovoth, Israel

WATER SUPPLY

16509; SEA; Tifton, Ga.

WATER USE EFFICIENCY

20867; SEA; Twin Falls, Idaho
19422; SEA; Sidney, Mont.
55218; Montana State University, Bozeman
24288; Texas A&M University, College Station
11176; Washington State University, Pullman

WATERSHEDS

5835; University of Arizona, Tucson
20755; SEA; Tucson, Ariz.
20756; SEA; Tucson, Ariz.
139; U.S. Forest Service; Riverside, Calif.
1269; Louisiana State University, Baton Rouge
1786; University of Minnesota, St. Paul
20762; SEA; Coshocton, Ohio
4487; Oklahoma State University, Stillwater
67518; Oregon State University, Corvallis
41949; SEA; Temple, Tex.
41950; SEA; Temple, Tex.
64993; Utah State University, Logan
152; U.S. Forest Service; La Crosse, Wis.
Nebraska, Omaha; Rogers
South Carolina, Clemson; Ligon

Table 2. Infiltration Research by Subject Matter Area within Major Categories[1]

1. INFILTRATION RESEARCH

Basic Theory

61852; Ecology and Climatology Agricultural Experiment Station; Connecticut
1373; Agronomy Department; Purdue University; Indiana

Green and Ampt Equation

61852; Ecology and Climatology Agricultural Experiment Station; Connecticut
18629; SEA; Boise, Idaho

Kostiakov Equation

66758; Water Science and Engineering Department; University of California, Davis

Unspecified and Miscellaneous Infiltration Equations

64706; Agricultural Engineering Department; University of Hawaii
1371; Agronomy Department; Purdue University; Indiana
19663; Israel (ARS Co-op Project)
Department of Agronomy and Soil Science; University of Hawaii; Green
SEA; Fort Collins, Colo.; Woolhiser
*SEA; Temple, Tex.; Burnett

Mathematical Simulation

20755; SEA; Tucson, Ariz.
61852; Ecology and Climatology Agricultural Experiment Station; Connecticut
18629; SEA; Boise, Idaho
1786; Agricultural Engineering Department; University of Minnesota
20762; SEA; Coshocton, Ohio
*68030; Agronomy Department; Oklahoma State
64832; Agricultural Engineering Department; Oregon State
*41949; SEA; Temple, Tex.
62941; Soil Science Department; University of Wisconsin
21346; Israel (SEA Co-op Project)
Agronomy Department; Mississippi State; Whisler
SEA; Fort Collins, Colo.; Woolhiser
SEA; Watkinsville, Ga.; Box
*43109; Agricultural Experiment Station; University of California, Davis
*42906; SEA; Pendleton, Oreg.

Instrumentation

32070; Agronomy and Soil Science Department; University of Hawaii
60187; Agronomy Department; Purdue University; Indiana
*66138; Soil and Crop Science Department; Texas A&M

[1]Numbers are CRIS accession numbers. See table 3 for list and complete identification of CRIS projects referenced. Last item on each line is correspondent's name. Lines without numbers refer to research descriptions received by mail. See table 4 for list of complete addresses.

*These projects have been planned but not implemented or refer to infiltration in CRIS plans but not in annual CRIS reports.

Table 2 (continued)

Spatial Variability and Areal Infiltration

5835; Department of Watershed Management; University of Arizona
2608; Water Science and Engineering Department; University of California, Davis
68217; Agronomy and Soil Science Department; University of Hawaii
Civil Engineering Department; University of Nebraska; Rodgers
SEA; Watkinsville, Ga.; Box
*SEA; Chickasha, Okla.; Frere

Partial Area Concept

5835; Department of Water Management; University of Arizona

Runoff/Infiltration Interface

20755; SEA; Tucson, Ariz.

Surface Factors

20755; SEA; Tucson, Ariz.

2. INFILTRATION MEASUREMENTS

W/Sprinkling Infiltrometer

5835; Department of Watershed Management; University of Arizona
18629; SEA; Boise, Idaho
1373; Agronomy Department; Purdue University; Indiana
40833; SEA; Ames, Iowa
55453; Agronomy Department; Iowa State
19422; SEA; Sidney, Mont.
55509; Agronomy Department; Cornell University; New York
20762; SEA; Coshocton, Ohio
*66138; Soil and Crop Science Department; Texas A&M University
65246; Soil Science and Biometry Department; Utah State
65076; Agronomy Department; Virginia Polytechnic Institute and State University
27364; Soil Science Department; University of Wisconsin
32018; Soil Science Department; University of Wisconsin
*64448; Soil Science Department; University of Wisconsin
19663; Israel (SEA Co-op Project)
Department of Agronomy and Soil Science; University of Hawaii; Green
Department of Agricultural Engineering; University of Idaho; Molnau
Division of Plant, Soil and Water Science; University of Nevada; Peterson
Department of Agronomy; Pennsylvania State; Cunningham
Water Resources Research Institute; Clemson University; Ligon
SEA; Fort Collins, Colo.; Woolhiser
*71005; Agronomy Department, Purdue University; Indiana
*69523; Agronomy Department; Iowa State
*69576; Agronomy Department; University of Kentucky
*42240; SEA; Morris, Minn.
*68030; Agronomy Department; Oklahoma State
*64644; Plant and Soil Science Department; University of Vermont
65510; Soil and Plant Nutrition Department; University of California; Davis
Department of Land, Air, and Water Resources; University of California, Davis; Singer

Table 2 (continued)

W/Flood Infiltrometers

5835; Department of Watershed Management; University of Arizona
32070; Agronomy and Soil Science Department; University of Hawaii
68217; Agronomy and Soil Science Department; University of Hawaii
Department of Agronomy and Soil Science; University of Hawaii; Green
Water Resources Research Institute; Kansas State; Powers
Department of Plant and Soil Sciences; University of Maine; Rourke
Water Resources Research Center; University of Maryland; Green
Department of Civil Engineering; University of Nebraska; Rogers
Soils Department; North Dakota State; Sweeney
Ohio Department of Natural Resources; Petro
Department of Agronomy; Pennsylvania State; Cunningham
Department of Agricultural Engineering; University of Tennessee; Sewell
Department of Agricultural and Irrigation Engineering; Utah State; Willardson

By Volume Balance

58968; Soils, Water and Engineering Department; University of Arizona
Soils Department; North Dakota State; Sweeney
Department of Agricultural Engineering; University of Tennessee; Sewell
Water Resources Research Institute; Clemson University; Ligon
68217; Agronomy and Soil Science Department; University of Hawaii
*55218; Plant and Soil Science Department; Montana State

By Unspecified Means

60735; Soils Department; Oregon State
143; U.S. Forest Service; Logan, Utah
63555; Agricultural and Irrigation Engineering Department; Utah State
64993; Range Science Department; Utah State
Department of Agricultural and Irrigation Engineering; Utah State; Willardson
Department of Agronomy and Soils; Washington State; Gardner
*8900; Soil and Plant Nutrition Department; University of California; Berkeley
*63382; Plant and Soil Science Department; University of Massachusetts
*22767; SEA; St. Paul, Minn.
*70678; Range Science Department; Texas A&M
*71317; Plant Science Department; University of West Virginia
*42735; Egypt (SEA Co-op Project)
Department of Agronomy, Mississippi State; Whisler
Department of Soil Science; University of Minnesota; Swann

Using Laboratory Columns

1189; Agronomy and Soil Science Department; University of Hawaii
Department of Agronomy; Pennsulvania State; Cunningham
*71279; Agronomy Department; New Mexico State

Calculate from Soil Parameters and Soil Water Movement

67918; Soil Science Department; North Carolina State
40385; Agricultural Experiment Station; Alabama
57173; Agricultural Engineering Department; Auburn University; Alabama
Water Resources Research Center; University of Maryland; Green

Table 2 (continued)

3. INFILTRATION AS A MODEL COMPONENT

Watershed Model

20758; SEA; Fort Collins, Colo.
1786; Agricultural Engineering Department; University of Minnesota
20762; SEA; Coshocton, Ohio
*41950; SEA; Temple, Tex.
Department of Agronomy and Soil Science; University of Hawaii; Green
*4487; Agricultural Engineering Department; Oklahoma State
*41949; SEA; Temple, Tex.
*SEA; West Lafayette, Ind.; Modenhauer

Soil Water Flow Model

18640; SEA; Fort Collins, Colo.
SEA; State College, Pennsylvania; Pionke

Hydro/Chemistry Model

40921; SEA; Watkinsville, Ga.
*70437; Soil Science Department; University of Florida

Surface Irrigation Model

66758; Water Science and Engineering Department; University of California, Davis
*43109; Agricultural Experiment Station; University of California, Davis

Irrigation-Nitrogen Transport Model

67103; Water Science and Engineering Department; University of California, Davis
62941; Soil Science Department; University of Wisconsin

Plant Models

Department of Agronomy; Mississippi State; Whisler
*67327; Agricultural Engineering Department; Clemson University

4. INFILTRATION EFFECTS (INDEPENDENT VARIABLE)

Nitrogen Removal

40694; SEA; Phoenix, Ariz.

Irrigation

58968; Soils, Water and Engineering Department; University of Arizona
64509; Soils, Water and Engineering Department; University of Arizona
*30831; Agricultural Experiment Station; New Mexico
SEA; Phoenix, Ariz.; Bouwer
*11176; Agronomy and Soils Department; Washington State

Crop Production

65664; Water, Science and Engineering Department; University of California, Davis
60735; Soils Department; Oregon State

Table 2 (continued)

Using Simulation

67103; Water, Science and Engineering Department; University of California, Davis
66758; Water, Science and Engineering Department; University of California, Davis
18640; SEA; Fort Collins, Colo.

Nitrogen Transformations

67103; Water, Science and Engineering Department; University of California, Davis
*61131; Agronomy Department; Pennsylvania State

Water Use Efficiency

19425; SEA; Fort Collins, Colo.

Phosphates

65149; Department of Soil and Plant Nutrition; University of California; Davis

Surface/Subsurface Water Yield

*16509; SEA; Tifton, Ga.

Rangeland

*67518; Animal Science Department; Oregon State

5. INFILTRATION RESPONSE (DEPENDENT VARIABLE)

Tillage

40385; Agricultural Experiment Station; Auburn, Ala.
10465; Department of Agronomy; Colorado State
18640; SEA; Fort Collins, Colo.
*71005; Department of Agronomy; Purdue University
40833; SEA; Ames, Iowa
19422; SEA; Sidney, Mont.
42016; Irrigation and Agricultural Research and Extension Center; Washington
27364; Soil Science Department; University of Wisconsin
*64448; Soil Science Department; University of Wisconsin
57173; Agricultural Engineering Department; Auburn University; Alabama
SEA; St. Paul, Minn.; Larson
SEA; Pendleton, Oreg.; Allmaras
SEA; Prosser, Wash.; Miller
SEA; Phoenix, Ariz.; Bouwer
*60689; Agricultural Engineering Department; Kansas State
*68197; Department of Agronomy; Kansas State
*69576; Department of Agronomy; University of Kentucky
*42906; SEA; Pendleton, Oreg.
*69608; Agronomy and Soils Department; Washington State
*41406; Yugoslavia (SEA Co-op Project)

Table 2 (continued)

Water Treatment Plant Effluent

32018; Soil Science Department; University of Wisconsin
18640; SEA; Fort Collins, Colo.
Institute of Water Research; Michigan State; Burton
Department of Agronomy; Pennsylvania; Cunningham
SEA; St. Paul, Minn.; Larson
SEA; Morgantown, W. Va., Bennett
64509; Soils, Water and Engineering Department; University of Arizona
64706; Agricultural Engineering Department; University of Hawaii
*23439; Department of Agronomy; University of Arkansas

Hydrophobic Soils

5835; Department of Watershed Management; University of Arizona
139; U.S. Forest Service; Riverside, Calif.
3824; Soil Science and Agricultural Engineering Department; University of California, Riverside
143; U.S. Forest Service; Logan, Utah

Soil and Water Parameters

55453; Department of Agronomy; Iowa State
59165; Soils Department; Oregon State
60573; Department of Agronomy; Virginia Polytechnic and State University
2608; Water Science and Engineering Department; University of California, Davis
Department of Agronomy and Soils; Washington State; Gardner
SEA; State College, Pennsylvania; Pionke
SEA; Bis Springs, Tex.; Fryrear
Water Resources Research Institute; Clemson University; Ligon
64509; Soils, Water and Engineering Department; University of Arizona
64706; Agricultural Engineering Department; University of Hawaii
65149; Department of Soil and Plant Nutrition; University of California; Davis

Crusts

18640; SEA; Fort Collins, Colo.
20762; SEA; Coshocton, Ohio
20799; Irrigation and Agricultural Research and Extension Center; Washington
19663; Israel (SEA Co-op Project)
Department of Agronomy; Mississippi State; Whisler
SEA; Oxford, Miss.; DeCoursey
*40910; SEA; Morris, Minn.
55453; Department of Agronomy; Iowa State
*68030; Department of Agronomy; Oklahoma State
*66138; Soil and Crop Science Department; Texas A&M

Biological Activity

*69523; Department of Agronomy; Iowa State

Strip Mine

61397; Ohio Agricultural Research and Development Center

Table 2 (continued)

Strip Mine (continued)

143; U.S. Forest Service; Logan, Utah
Department of Agronomy; Pennsylvania State; Cunningham
SEA; Morgantown, W. Va.; Bennett
*70190; Department of Agronomy; Iowa State
*69576; Department of Agronomy; University of Kentucky
*69578; Ohio Agricultural Research and Development Center

Soil Cracks

1269; Agricultural Engineering Department; Louisiana State
*64644; Plant and Soil Science Department; University of Vermont

Land Surface Treatment

18926; SEA; Brawley, Calif.
55509; Agronomy Department; Cornell University; New York
32018; Soil Science Department; University of Wisconsin
19422; SEA; Sidney, Mont.
24288; Agricultural Experiment Station; Texas
20799; Irrigation and Agricultural Research and Extension Center; Washington
SEA; Tucson, Ariz.; Dixon

Water Harvest

SEA; Phoenix, Ariz.; Bouwer

Soil Amendment

66136; Department of Agronomy; New Mexico State
60735; Soils Department; Oregon State
60573; Department of Agronomy; Virginia Polytechnic and State University
20799; Irrigation and Agricultural Research and Extension Center; Washington
61302; Soil Science Department; University of Wisconsin
19663; Israel (SEA Co-op Project)
Department of Agronomy; Pennsylvania State; Cunningham
*71279; Department of Agronomy; New Mexico State
*69578; Ohio Agricultural Research and Development Center

Frost

61645; Department of Agronomy; Cornell University; New York
67506; Soils Department; North Dakota State
152; U.S. Forest Service; La Crosse, Wis.

Public Use

*66086; Ohio Agricultural Research and Development Center

Rangeland

64993; Range Science Department; Utah State
*30927; Department of Agronomy; Pennsylvania State
*70678; Range Science; Texas A&M

Table 2 (continued)

Forest Soils

152; U.S. Forest Service, La Crosse, Wis.

Seasonal

62941; Soil Science Department; University of Wisconsin
20755; SEA; Tucson, Ariz.

Table 3. Infiltration-Related CRIS Work Units in Numerical Order of Their Accession Numbers

139; Flood and Sediment Reduction in Steep Unstable Brushlands of the Southwest; C. E. Conrad; Pacific Southwest Forest and Rangeland Experiment Station; Riverside, CA 92507

143; Mine Spoil Reclamation in the Intermountain and Northern Rocky Mountain Regions (WMR); P. E. Packer; Utah State University; Logan, UT 84321

152; Sustaining High-Quality Water Yields from Forested Watersheds in the North-Central States; R. S. Sartz; North Central Forest Experiment Station; La Crosse, WI 54601

1189; Soil Water and Its Management in the Field; G. Uehara; University of Hawaii; Honolulu, HI 96822

1269; Factors Affecting Water Yields from Small Watersheds and Shallow Ground Aquifers; H. J. Braud; Louisiana State University; Baton Rouge, LA 70803

1373; Water Movement in Rigid and Swelling Soils; D. Swartzendruber; Purdue University; West Lafayette, IN 47907

1786; Hydrology of Small Watersheds; C. L. Larson; University of Minnesota; St. Paul, MN 55108

2608; Soil Water and Its Management in the Field; D. R. Nielsen; University of California; Davis, CA 95616

3824; The Role of Soil Wettability on Water Movement; J. Letey; University of California; Riverside, CA 92507

4394; Soil Colloids in Relation to Pacific Northwest Soil and Water Management Problems; J. L. Young; Oregon State University; Corvallis, OR 97331

4487; Runoff Characteristics of Agricultural Areas; F. R. Crow; Oklahoma State University; Stillwater, OK 74074

5835; Infiltration Capacities on Managed Watersheds; M. J. Zwolinski; University of Arizona; Tucson, AZ 85721

8900; Relationship Between Irrigation Water Composition and Soil Properties; K. L. Babcock; University of California; Berkeley, CA 94720

10465; Effect of Soil and Crop Management on Yield and Quality of Sugar Beets; W. R. Schmehl; Colorado State University; Fort Collins, CO 80521

11176; Soil Water and Its Management in the Field; W. H. Gardner; Washington State University; Pullman, WA 99163

16509; Surface and Subsurface Farm Water Supplies in the Southern Coastal Plains; L. E. Asmussen; USDA-SEA-AR; P. O. Box 946, Tifton, GA 31794

Table 3 (continued)

18629; Ground Water in Relation to Management of Rangeland Watersheds in the Northwest; D. L. Brakensiek; USDA-SEA-AR; P. O. Box 2700, Boise, ID 83301

18640; Measurement and Prediction of Soil Water Movement; A. Klute; Colorado State University; Fort Collins, CO 80521

18926; Chemistry and Nutrient Availability and Movement in Soils of the Imperial Valley; C. F. Ehlig; USDA-SEA-AR; 4151 Highway 86, Brawley, CA 92227

18928; Tillage and Residue Practices for Erosion Control in the Northwest; R. E. Ramig; USDA-SEA-AR; P. O. Box 370, Pendleton, OR 97801

19422; Methods to Increase Precipitation-Use Efficiency by Forage on Rangelands, J. R. Wight; USDA-SEA-AR; P. O. Box 1109, Sidney, MT 59270

19425; Water Conservation by Land Forming and Manipulation of Soil Properties; H. R. Gardner; USDA-SEA-AR; Colorado State University, Fort Collins, CO 80521

19663; Infiltration and Rainfall Runoff as Affected by Natural and Artificial Surface Crusts; D. Hillel; Hebrew University of Jerusalem; Rehovoth, Israel

20755; Improving Water and Erosion Control and Channel Stabilization on Semiarid Rangeland Watersheds; D. L. Chery, Jr.; USDA-SEA-AR; 442 East Seventh Street, Tucson, AZ 85705

20756; Predicting Runoff and Streamflow from Watersheds in the Southwest; K. G. Renard; USDA-SEA-AR; 442 East Seventh Street; Tucson, AZ 85705

20758; Simulation of Hydrologic Systems; D. A. Woolhiser; USDA-SEA-AR; Colorado State University, Fort Collins, CO 80521

20762; Predicting Runoff and Streamflow from Agricultural Watersheds in the North Appalachian Region; W. R. Hamon; USDA-SEA-AR; P. O. Box 478, Coshocton, OH 43812

20799; Infiltration Control and Soil Water Redistribution in Relation to Irrigation; D. E. Miller, USDA-SEA-AR; Prosser, WA 99350

20867; Efficient Water Use on Nonirrigated Crop and Rangeland; H. F. Mayland; USDA-SEA-AR; Route 1, Box 186, Twin Falls, ID 83341

21346; Development of Methods, Tools and Solutions for Unsaturated Flow Applications, Watershed Hydrology; G. Dagan; Technion Research and Development Foundation; Haifa, Israel

22767; Effect of Tilled Soil Structure on Water Transmission Properties and Soil Detachment; W. P. Martin, USDA-SEA-AR; University of Minnesota, St. Paul, MN 55108

23439; Mineral Analysis of Water; L. H. Hileman; University of Arkansas; Fayetteville, AR 72701

Table 3 (continued)

24288; Interrow Watersheds as a Means of Increasing Rainfall Efficiency; J. F. Mulkey, Jr.; Texas A & M University; College Station, TX 77843

27364; Soil and Water Management Systems in the Upper Mississippi Valley; A. E. Peterson; University of Wisconsin; Madison, WI 53706

30831; Determining Design Lengths of Run for Surface Irrigation and Infiltration Rates for Sprinkler Irrigation; A. E. Stewart; Agricultural Experiment Station; NM 87401

30927; Long Time Effects of Variations in Soil and Crop Management Systems; A. S. Hunter; Pennsylvania State University; University Park, PA 16802

32018; Runoff Measured by Simulated Rainfall After Treatment with Animal Waste, Liquid Sludge and Residues; A. E. Peterson; University of Wisconsin; Madison, WI 53706

32070; Hydrologic Characteristics of Benchmark Soils of Hawaii's Forest Watersheds; S. A. El-Swaify; University of Hawaii; Honolulu, HI 96822

32447; Crop and Soil Management With and Without Supplemental Water; L. O. Fine; South Dakota State University; Brookings, SD 57006

40385; Relation of Soil Tilth to the Transport of Water and Dissolved Substances Through the Root Zone; A. E. Hiltbold; Auburn University; Auburn, AL 36830

40694; Management of Subsurface Water Movement Systems for Renovation and Conservation of Water; H. Bouwer; USDA-SEA-AR; 4331 East Broadway, Phoenix, AZ 85040

40768; Source and Magnitude of Sediment Yield from Watersheds; C. K. Mutchler; USDA-SEA-AR; P. O. Box 5367, State College, MS 39762

40833; Soil and Water Loss as Related to Tillage Systems of Iowa Soils; J. M. Laflen; USDA-SEA-AR; Iowa State University, Ames, IA 50011

40910; Techniques for Improving Soil Structure Stability and Their Effect on Erosion and Infiltration; R. F. Holt; USDA-SEA-AR; Morris, MN 56267

40921; Mathematical Modeling of Systems that Regulate Effluent of Applied Chemical from Agricultural Lands; R. R. Bruce; USDA-SEA-AR; Watkinsville, GA 30677

41406; Changes of Physical Properties of Soil Effected by Different Agricultural Systems; Z. Bogosav; Institute for Agricultural Research; Novi Sad, Yugoslavia

41853; Modeling Soil-Plant-Atmosphere Relations for Agricultural Plant Communities; J. T. Ritchie; USDA-SEA-AR; P. O. Box 748, Temple, TX 77840

41949; Modeling Hydrologic Processes on Agricultural Watersheds in Western Gulf Region; C. W. Richardson; USDA-SEA-AR; P. O. Box 748, Temple, TX 77840

Table 3 (continued)

41950; Modeling Surface Runoff from Complex Watersheds; J. R. Williams; USDA-SEA-AR; P. O. Box 748, Temple, TX 77840

42016; Infiltration, Erosion Control and Soil Water Movement in Relation to Irrigation; D. E. Miller, USDA-SEA-AR; Prosser, WA 99350

42240; Mechanics and Control of Soil Erosion by Water - Barnes and Associated Soils; R. A. Young; USDA-SEA-AR; Morris, MN 56267

42735; Field Evaluation of Pipe and Envelope Materials for Draining Water-logged Soils; A. I. Elshabassy; Ministry of Agriculture; Giza, Egypt

42906; Tillage, Residue, and Traffic Hardpan Effects on Water Erosion, Infiltration and Evaporation; R. R. Allmaras; USDA-SEA-AR; P. O. Box 370, Pendleton, OR 97801

43109; Irrigation Advance and Recession Modeling; T. Strelkoff; USDA-SEA-AR; University of California; Davis, CA 95616

55218; Efficiency of Soil Water Storage and Use for Crop Production in the Semi-Arid Areas; H. M. Ferguson; Montana State University; Bozeman, MT 59715

55453; Soil Erosion and Infiltration as Functions of Cropping, Clod Breakdown and Soil Forming; P. Rosenberry; Iowa State University; Ames, IA 50011

55509; Agricultural Contributions to Nutrients in Water; P. J. Zwerman; Cornell University; Ithaca, NY 14850

57173; Development and Evaluation of Tillage and Other Practices in Controlled Traffic System for Cotton; W. T. Dumas, Jr.; Auburn University; Auburn, AL 36830

58064; Hydraulic Properties of Agricultural Soils; W. E. Hedstrom; University of Wyoming; Laramie, WY 82070

58968; Hydraulics of Furrow Irrigation; D. D. Fangmeier; University of Arizona; Tucson, AZ 85721

59165; Clay Mineralogy of Soils Developed on Volcanic Parent Materials; M. E. Harward; Oregon State University; Corvallis, OR 97331

60187; Characterization of Amorphous Material in Soils; C. B. Roth; Purdue University; West Lafayette, IN 47907

60573; Correlation of Soil Volume Change and Permeability with other Physical Characteristics; D. F. Amos; Virginia Polytechnic Institute; Blacksburg, VA 24061

60689; Tillage Systems for Grain Sorghum Production; S. J. Clark; Kansas State University; Manhattan, KS 66504

Table 3 (continued)

60735; Irrigation Scheduling of Agricultural Crops; C. H. Ullery; Oregon State University; Corvallis, OR 97331

61131; Nitrates in Soil, Water and Plants; D. E. Baker; Pennsylvania State University; University Park, PA 16802

61302; Effect of Whey on Soil and Plant Growth and on Water Runoff and Erosion; A. E. Peterson; University of Wisconsin; Madison, WI 53706

61397; Soil Development and Forest Productivity on Ohio Strip-mine Spoils; J. P. Vimmerstedt; Ohio Agricultural Research and Development Center; Wooster, OH 44691

61645; Phase Equilibria and Transitions in Porous Media Including Soil Freezing and Frost Heaving; R. D. Miller; Cornell University; Ithaca, NY 14850

61852; Water Movement in Layered Soils; J. Y. Parlange; Connecticut Agricultural Experiment Station; New Haven, CT 06504

62941; Correlation of Nitrate and Solute Leaching with Climate; W. R. Gardner; University of Wisconsin; Madison, WI 53706

63382; Soil Modification with Aggregating Agents and Cultivating Practices of Turfgrass Soil; R. N. Carrow; University of Massachusetts; Amherst, MA 01002

63555; Surface Irrigation Optimization in the Great Basin; G. E. Stringham; Utah State University; Logan, UT 84321

64448; Influence of Tillage and Planting Methods on Movement of Nutrients, Herbicides, Water, and Soil; A. E. Peterson; University of Wisconsin; Madison, WI 53706

64509; Trickle Irrigation to Improve Crop Production and Water Management; D. D. Fangmeier; University of Arizona; Tucson, AZ 85721

64644; The Suitability of Heavy Clay Soils for Waste Disposal; F. R. Magdoff; University of Vermont; Burlington, VT 05401

64706; Trickle Irrigation to Improve Crop Production and Water Management; I-Pai Wu; University of Hawaii; Honolulu, HI 96822

64832; Trickle Irrigation to Improve Crop Production and Water Management; M. N. Shearer; Oregon State University; Corvallis, OR 97331

64993; Hydrology of Pinyon-Juniper Woodlands and Associated Forest-Range; G. F. Gifford; Utah State University; Logan, UT 84321

65076; Producing Vegetation on Steep Slopes Concurrently With and Subsequent to Highway Construction; R. E. Blaser; Virginia Polytechnic Institute and State University; Blacksburg, VA 24061

Table 3 (continued)

65149; Trickle Irrigation to Improve Crop Production and Water Management; D. E. Rolston; University of California; Davis, CA 95616

65246; Salinity Management in the Colorado River Basin; J. J. Jurinak; Utah State University; Logan, UT 84321

65664; Water Management of Some Vegetable Crops on Slowly Permeable Soils; D. W. Grimes; University of California; Davis, CA 95616

66086; Forest and Recreation Resources in the North Central United States; T. R. Mitchell; Ohio Agricultural Research and Development Center; Wooster, OH 44691

66136; Calcium Carbonate Equilibria in Soils and Irrigation Waters; G. A. O'Connor; New Mexico State University; Las Cruces, NM 88003

66138; Established Relationships Between Crusting Characteristics and Seedling Emergence Forces; K. W. Brown; Texas A & M University; College Station, TX 77843

66510; Studies in Soil Erosion and Soil Erodibility; G. L. Huntington; University of California; Davis, CA 95616

66758; Prediction of Surface Irrigation Performance--Mathematical Models; T. S. Strelkoff; University of California; Davis, CA 95616

67103; Computer Modeling of Nitrogen Transformations and Transport in Cropped, Irrigated Lands; K. K. Tanji; University of California; Davis, CA 95616

67327; Simulation of Processes in the Rhizosphere; J. R. Lambert; Clemson University; Clemson, SC 29631

67506; Effect of Soil Freezing on Water Infiltration and Runoff; J. S. Bauder; North Dakota State University; Fargo, ND 58103

67518; Range Watershed Management; J. C. Buckhouse; Oregon State University; Corvallis, OR 97331

67918; An Evaluation of Soil Physical and Chemical Properties of Coastal Plain Soils; D. K. Cassel; North Carolina State University, Raleigh, NC 27607

68030; Water Infiltration as Influenced by Soil Crusts or Seals; D. L. Nofziger; Oklahoma State University; Stillwater, OK 74074

68197; Effect of Reduced Tillage on Soil Properties; J. A. Hobbs; Kansas State University; Manhattan, KS 66504

68217; Hydrologic Characteristics of Selected Forest Watershed Soils; S. A. El-Swaify; University of Hawaii; Honolulu, HI 96822

Table 3 (continued)

69523; Soil Permeability Relationships with Microbial Activity and Other Soil Properties; F. R. Troeh; Iowa State University; Ames, IA 50011

69576; Reclamation of Surface Mined Coal Spoils; R. I. Barnhisel; University of Kentucky; Lexington, KY 40506

69578; Use of Sludges and Top Soil in Reclamating Coal Strip-Mine Spoils; F. Haghiri; Ohio Agricultural Research and Development Center; Columbus, OH 43216

69608; Runoff, Soil Erosion, and Quality of Runoff Water as Affected by Bluegrass Seed Production; D. K. McCool; Washington State University; Pullman, WA 99163

70190; Hydrologic Management in Strip Mining; D. Kirkham; Iowa State University; Ames, IA 50011

70437; Development of Hydrologic/Water Quality Models for Agriculture and Forestry; R. S. Mansell; University of Florida; Gainesville, FL 32601

70678; Impacts of Range Improvement Practices on Infiltration Rates and Erosion; W. H. Blackburn; Texas A & M University; College Station, TX 77843

71005; Tillage-Mulch Effects on Erosion and Infiltration; W. C. Moldenhauer; Purdue University; West Lafayette, IN 47907

71279; The Use of Soil Amendments for Establishing Vegetation on Sodic and/or Coaly Spoils in Arid Area; W. I. Gould; New Mexico State University; Las Cruces, NM 88003

71317; Soil Water Relations and Root Development on Characterized Classes of Mine Soils; R. M. Smith; West Virginia University; Morgantown, WV 26506

Table 4. Addresses of Infiltration Correspondents Alphabetically by States

Arizona

Herman Bouwer; USDA-SEA-AR, Water Conservation Lab.; 4331 East Broadway; Phoenix 85040

Robert M. Dixon; USDA-SEA-AR, Southwest Rangeland Watershed Research Center; 442 East Seventh Street; Tucson 85705

Arkansas

E. Moye Rutledge; University of Arkansas, Department of Agronomy; 110 Agriculture Building; Fayetteville 72701

Table 4 (continued)

California

Michael J. Singer; University of California, Department of Land, Air and Water Resources; Hoagland Hall; Davis 95616

Christiaan Dirksen; USDA-SEA-AR, Salinity Laboratory; 4500 Glenwood Drive, P.O. Box 672; Riverside 92502

Colorado

Roger E. Smith; USDA-SEA-AR, Colorado State University, Engineering Research Center; Foothills Campus; Fort Collins 80523

Georgia

Loris E. Asmussen; USDA-SEA-AR, Southeast Watershed Research Center; P. O. Box 946; Tifton 31794

R. Russell Bruce; USDA-SEA-AR, Southern Piedmont Conservation Research Center; P. O. Box 555; Watkinsville 30677

Hawaii

R. E. Green; University of Hawaii, Department of Agronomy and Soil Science; 3190 Maile Way; Honolulu 96822

Idaho

Donald L. Brakensiek; USDA-SEA-AR, Northwest Watershed Research Center; 1175 South Orchard - Patti Plaza; Boise 83705

Marvin E. Jensen; USDA-SEA-AR, Snake River Conservation Research Center; Route 1, Box 186; Kimberly 83341

Myron Molnau and Gary D. Bubenzer; University of Idaho, Department of Agricultural Engineering; Moscow 83843

Illinois

Glenn E. Stout; University of Illinois, Water Resources Center; 2535 Hydrosystems Laboratory; Urbana 61801

Indiana

W. C. Moldenhauer; USDA-SEA-AR, Purdue University; Agronomy Department, Lilly Hall; West Lafayette 47907

Dan Wiersma; Purdue University, Water Resources Research Center; Lilly Hall; West Lafayette 47907

Table 4 (continued)

Kansas

Leon Lyles; USDA-SEA-AR, Kansas State University; Agronomy Department, R-204, East Waters Hall; Manhattan 66506

William L. Powers; Kansas State University, Water Resources Research Institute; Waters Annex; Manhattan 66506

Louisiana

Guye H. Willis and Cade E. Carter; USDA-SEA-AR; P. O. Drawer U, University Station; Baton Rouge 70893

Maine

Robert V. Rourke; University of Maine, Department of Plant and Soil Sciences; Deering Hall; Orono 04473

Joseph Bornstein; USDA-SEA-AR, University of Maine; New England Plant, Soil and Water Laboratory; Orono 04473

Maryland

R. L. Green; University of Maryland, Water Resources Research Center; College Park 20742

Yaron Sternberg; University of Maryland, Civil Engineering Department; College Park 20742

Edward Strickling; University of Maryland, Department of Agronomy; College Park 20742

Michigan

Thomas M. Burton; Michigan State University, Institute of Water Research; Natural Resources Building; East Lansing 48824

Minnesota

Curtis L. Larson; University of Minnesota, Department of Agricultural Engineering; St. Paul 55108

James B. Swan; University of Minnesota, Department of Soil Science; 1529 Gortner Avenue; St. Paul 55108

W. E. Larson; USDA-SEA-AR, University of Minnesota; 1529 Gortner Avenue, 201 Soil Science Building; St. Paul 55108

John J. Waelti; University of Minnesota, Water Resources Research Center; 107 Hubbard Building, 2675 University Avenue; St. Paul 55114

Table 4 (continued)

Mississippi

F. D. Whisler; Mississippi State University, Department of Agronomy; P. O. 3190 Maile Way; Honolulu 96822

M. J. M. Römkens; USDA-SEA-AR, Sedimentation Laboratory; P. O. Box 1157; Oxford 38655

Montana

Thomas J. Nimlos; University of Montana, School of Forestry; Missoula 59801

Nebraska

W. F. Rogers; University of Nebraska, Department of Civil Engineering; P. O. Box 688; Omaha 68101

Nevada

Frederick F. Peterson; University of Nevada, Division of Plant, Soil and Water Science; Reno 89557

New Hampshire

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